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RESEARCH MEMORANDUM

THE EFFECT OF HIGH SOLIDITY ON PROPELLER CHARACTERISTICS

AT HIGH FORWARD SPEEDS FROM WIND-TUNNEL TESTS OF THE

NACA 4-(3)(06.3)-06 AND NACA 4-(3)(06.4)-09

TWO-BLADE PROPELLERS

By

James B. Delano

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
February 27, 1947

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RESEARCH MEMORANDUM

THE EFFECT OF HIGH SOLIDITY ON PROPELLER CHARACTERISTICS AT HIGH FORWARD SPEEDS FROM WIND-TUNNEL TESTS OF THE NACA 4-(3)(06.3)-06 AND NACA 4-(3)(06.4)-09 TWO-BLADE PROPELLERS

By James B. Delano

SUMMARY

Tests of two-blade propellers having the NACA 4-(3)(06.3)-06 and NACA 4-(3)(06.4)-09 blade designs (blade activity factors of 179 and 265, respectively) have been made in the Langley 8-foot high-speed tunnel through a range of blade angle from 20° to 70° for free-stream Mach numbers from 0.165 to 0.725 to determine the effects of high solidity and compressibility on propeller characteristics. The tests are part of a general investigation of propellers at high forward speeds. Results previously reported for similar tests of two-blade propellers having the NACA 4-308-03 and NACA 4-308-045 blade designs (blade activity factors of 87 and 133, respectively) are included for comparison.

The results showed that the 0.06- and 0.09-solidity blades, although producing efficiencies of the order of 90 percent, were less efficient than blades of conventional solidity. The variation in average blade lift coefficient with solidity at a constant blade angle and advance-diameter ratio through the speed range of these tests was found to be analogous to the variation of wing lift coefficient with aspect ratio, indicating that high-solidity blades may be desirable at very high speeds. Because of power limitations of the test equipment, conclusive evidence of the possible favorable effects of increased blade solidity at high speeds was not obtained. Further tests are desirable.

INTRODUCTION

The NACA has conducted in the Langley 8-foot high-speed tunnel a general investigation of propellers operating at high forward

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speeds and high rotational tip speeds in an attempt to improve propeller performance. Results of this investigation covering the effects of compressibility, solidity, and camber are presented in references 1, 2, and 3 as parts I, II, and III of this general investigation.

In addition to the propellers already tested, two very high-solidity two-blade propellers with thinner outboard sections were tested at the same time. The results were not included in the report on "effects of compressibility and solidity," reference 2, because speed and power limitations prevented reaching conditions at which the adverse effects of compressibility occur. However, in light of the favorable high-speed results obtained with wings of low aspect ratio it was believed that the results of the investigation of very wide blade propellers would be of interest. The blade solidity for one propeller was 0.06 (design blade angle approximately 45°) and for the other propeller it was 0.09 (design blade angle approximately 60°). These solidities are roughly two and three times those of conventional width blades.

The results of this investigation are presented herein as the fourth part of the general investigation of propellers at high speeds.

APPARATUS AND METHODS

The apparatus and methods described in reference 1 were used in the tests reported here. The tests were conducted in the Langley 8-foot high-speed tunnel. A photograph showing the model setup is given as figure 1.

Model propellers.- Two 2-blade propellers of 4-foot diameter utilizing NACA 16-series sections were designed having the blade-form characteristics shown in figure 2. These propellers are designated as the NACA 4-(3)(06.3)-06 and 4-(3)(06.4)-09 propellers having activity factors of 179 and 265 per blade, respectively. The system of designation is explained in reference 3. Both propellers have essentially the same thickness ratio. A photograph of the blades is given in figure 3. The NACA 4-(3)(06.3)-06 propeller has the same pitch distribution as the NACA propellers described in references 1 to 3. The propellers were designed to give minimum induced losses assuming the blades to be lightly loaded. The design conditions for these propellers are given as follows:

	NACA 4-(3)(06.3)-06	NACA 4-(3)(06.4)-09
Tip Mach number	0.92	0.95
Lift coefficient at 0.7-radius station	0.3	0.3
Advance-diameter ratio	2.11	3.70
Nominal design blade angle at 0.7-radius station	45°	60°

The NACA 4-308-03 and 4-308-045 propellers, references 1 and 2, have the same design conditions as listed above for the NACA 4-(3)(06.3)-06 propeller.

The range of tests was the same, within speed and power limitations, as those of references 1 to 3. The range of blade angle and free-stream Mach number is given below:

NACA 4-(3)(06.3)-06 PROPELLER

Free-stream Mach number, M	Blade angle at 0.75-radius station, $\beta_{0.75R}$ (deg)								
0.165	20	25	30	35	40	45	50	55	60
.23			30	35	40	45	50	55	60
.35				35	40	45	50	55	60
.43					40	45	50	55	60
.53						45	50	55	60
.60							50	55	60
.65							50	55	60
.675								55	60
.700								55	60

NACA 4-(3)(06.4)-09 PROPELLER

Free-stream Mach number, M	Blade angle at 0.75-radius station, $\beta_{0.75R}$ (deg)										
0.165	20	25	30	35	40	45	50	55	60	65	70
.23			30	35	40	45	50	55	60	65	70
.35						45	50	55	60	65	70
.43							50	55	60	65	70
.53								55	60	65	70
.60									60	65	70
.65									60	65	70
.675									60	65	70
.700										65	70
.725										65	70

SYMBOLS AND REDUCTION OF DATA

The data have been corrected for tunnel-wall effects, horizontal buoyancy, and blower-spinner effects in the same manner as the data in references 1 to 3. The thrust used is propulsive thrust. The symbols and definitions used herein are as follows:

A. F. propeller activity factor

B number of blades

b blade width, feet

b/D section blade width ratio

C_L section lift coefficient; wing lift coefficient

C_{L_D} section design lift coefficient

$\bar{C}_L$	average lift coefficient for propeller (see reference 6)
C_P	power coefficient $\left(\frac{P}{\rho n^3 D^5}\right)$
C_T	thrust coefficient $\left(\frac{T}{\rho n^2 D^4}\right)$
D	propeller diameter, feet
h	blade section maximum thickness, feet
h/b	blade section thickness ratio
J	advance-diameter ratio (V/nD)
M	free-stream Mach number
M_t	helical tip Mach number $M\sqrt{1 + \left(\frac{\pi}{J}\right)^2}$
n	propeller rotational speed, rps
P	power, foot pounds per second
R	propeller tip radius, feet
r	radius to a blade element, feet
T	thrust, pounds
V	free-stream velocity, fps
x	blade station, r/R
β	section blade angle, degrees
$\beta_{0.75R}$	blade angle at 0.75-radius station, degrees
η	propeller efficiency $\left(\frac{C_T J}{C_P}\right)$
ρ	air density, slugs per cubic foot
σ	solidity $\left(\frac{Bb}{2\pi r}\right)$ value at 0.7-radius station is used herein

Subscript:

1 refers to conditions at maximum efficiency for $M_t \approx 0.25$

RESULTS AND DISCUSSIONS

The basic characteristics of the two-blade NACA 4-(3)(06.3)-06 and 4-(3)(06.4)-09 propellers are presented in figures 4 and 5, respectively. Curves of the resultant tip Mach number M_t are also shown in the same figures.

Maximum efficiency.- The envelope efficiencies for both propellers are presented in figure 6 for free-stream Mach numbers from 0.165 to 0.725. For comparison, results are also shown for the NACA 4-308-03 and 4-308-045 propellers, references 1 and 2. Maximum efficiencies of over 90 percent were obtained for blade solidities above 0.045. However, the maximum efficiencies for the 0.09-solidity blade are always lower, and for the 0.06-solidity blade generally lower, than those for the 0.03 and 0.045-solidity blades throughout the speed range. For the low range of advance-diameter ratio the 0.06-solidity blade produced efficiencies as much as 3 percent higher than those for the 0.09-solidity blade for free-stream Mach numbers through 0.35. At the higher values of Mach number and advance-diameter ratio the efficiencies were as much as 6 percent higher for the 0.06-solidity blade, the differences decreasing at the very high values of advance-diameter ratio. This difference in efficiency is attributed to the more favorable pitch distribution of the 0.09-solidity blade for the higher pitch range.

Of particular interest are the high values of maximum efficiency, above 90 percent, which have been obtained in this investigation and those reported in references 1 to 3. These results are due to the detailed attention given to the design of the propellers and to the test setup. These details include the following:

(a) The design was made to give minimum induced losses for light loadings.

(b) The blade shank sections were thin.

(c) High critical speed NACA 16-series sections were used throughout.

(d) Manufacturing tolerances were kept small.

(e) The gaps between the spinner and blades were sealed.

(f) Test speeds were kept below the critical speeds of test body and supports.

Tuft surveys over the test body and supports gave no indication of flow separation with or without the propeller.

These high efficiencies indicate a reduction in the rotational losses associated with an isolated propeller. The induced efficiency losses for operation at the design conditions for these propellers in an isolated configuration are shown in figure 7 plotted against blade solidity. The rotational induced loss at the design condition is 7 percent for the 0.09-solidity blade propeller ($J = 3.7$), and 2.9 percent for the 0.06-solidity blade propeller ($J = 2.11$). Possibly the dynamometer supports (20-inch chord) used in this investigation were effective in converting rotational energy into thrust. Betz shows theoretically in reference 4 that the use of contra-vanes of optimum design for a test setup such as used in this investigation might convert into thrust 60 to 80 percent of the rotational energy normally lost. Calculations of the drag power loss for the design conditions of these propellers show that, if about 50 percent of the rotational energy were recovered, the measured and calculated efficiencies would be in excellent agreement. Reference 5 shows that approximately 50 percent of the rotational energy can be recovered.

Effect of blade solidity on power coefficient and power coefficient-solidity ratio for high efficiency.- The range of power coefficient and power coefficient-solidity ratio for which high efficiencies are possible is illustrated in figure 8 against advance-diameter ratio and blade solidity. An efficiency contour of 86 percent for each propeller was arbitrarily chosen. The value of the power coefficient or power coefficient-solidity ratio within the efficiency contour corresponds to efficiencies above 86 percent; the values for maximum efficiency are also shown. Changes in free-stream Mach number had no great effect upon the contours; hence only the results for $M = 0.165$ are presented. High-solidity blades operate at higher power coefficients than low-solidity blades, figure 8(a), but the increase in power coefficient is not in direct proportion to the increase in blade solidity. At low values of advance-diameter ratio the change in power coefficient is approximately the same for all the blades, whereas at the high advance-diameter ratios the change in power coefficient for the 0.09-solidity blade is approximately only double that for the 0.03-solidity blade.

Figure 8(b) shows that low-solidity blades produce higher power coefficients per unit of blade solidity than high-solidity blades. At low values of advance-diameter ratio the change in power coefficient-solidity ratio for the 0.03-solidity blade is about three times that for the 0.09-solidity blade, whereas at the high advance-diameter ratios the change for the 0.03-solidity blade is about $1\frac{1}{2}$ times that for the 0.09-solidity blade. Because of the fact that in these tests of two-blade propellers the local induced velocities were much greater for the high-solidity blades it is not possible to draw a definite conclusion that a propeller with many narrow blades is superior to one of equal total solidity having few wide blades. Additional tests are needed to establish definitely the interrelation of number of blades and total solidity.

Effect of power coefficient and advance-diameter ratio on efficiency.- The variation of efficiency with power coefficient is shown in figure 9 for several values of advance-diameter ratio for a Mach number of 0.165. Blades of high solidity are more efficient than blades of low solidity at high power coefficients as would be expected because the blades of low solidity would be stalled. Conversely, blades of low solidity are more efficient than blades of high solidity at low power coefficients because blades of high solidity would be too lightly loaded. The higher efficiencies shown for the 0.045-solidity blade compared to the 0.03-solidity blade even at low values of power coefficient and advance-diameter ratio are within experimental accuracy.

Figure 10 has been plotted from figure 9 to show the approximate operating range in which a blade of given solidity is more efficient than any other blade. These curves should be considered generally to give only a qualitative comparison. The region in which a given two-blade propeller is the most efficient one is indicated by its blade-solidity designation. No line representing the upper limit is shown for the 0.09-solidity blade because no higher solidity blades were tested.

Compressibility effects.- A comparison of the relative maximum efficiencies versus tip Mach number and free-stream Mach number for the approximate design blade angle is shown in figure 11 for both propellers. No adverse compressibility effects occurred for the 0.06-solidity blade at least up to a tip Mach number of 0.93. Similar results were obtained for the NACA 4-308-045 propeller, reference 2. For the 0.09-solidity blade, losses in maximum efficiency started at tip Mach numbers as low as 0.55 and increased gradually with an increase in speed so that at a tip Mach number of approximately 0.90 the loss in maximum efficiency was 5 percent.

At a given tip Mach number for the operating conditions shown in figure 11, the resultant section speeds, particularly at the inboard sections, are highest for the 0.09-solidity blade. Consequently earlier compressibility losses at the shank sections would be expected for this blade. Computation of the section speeds indicates that for free-stream Mach numbers where the efficiency curve for the 0.09-solidity blade diverges, no adverse compressibility effects should be expected to occur but that such effects would be expected to occur at the shank sections for free-stream Mach numbers between 0.65 and 0.675. It is estimated that the effect of the small leading edge fairing at the shank sections of this blade (see fig. 1) and any detrimental effect due to air leakage between spinner and blades (if such leakage occurred) would result in an efficiency loss of not more than 1 to 2 percent. Consequently, it is believed that the efficiency losses that occur are primarily due to the use of very wide blades.

The effect of compressibility on the power coefficient for maximum efficiency at the design blade angle and advance-diameter ratio for each propeller is shown in figure 12 as plots of relative power coefficient versus tip Mach number. These conditions approximate very closely the conditions for which the maximum efficiencies were presented in figure 11. The rate of increase in power coefficient with Mach number decreases with increase in blade solidity.

A comparison of the average lift coefficient for propellers and wings through the speed range is shown in figure 13. The average lift coefficients for the propellers were computed using the method presented in reference 6, and are for the design blade angle and advance-diameter ratio for each propeller. The lift coefficients for wings of different aspect ratio were obtained from tests made in the Langley 24-inch high-speed tunnel. The effects in both cases are very similar. As the propeller blade width is increased (aspect ratio decreased) the magnitude of the changes decreases and the onset of adverse compressibility effects is delayed as is shown for the NACA 4-308-045 propeller. Based on the analogy shown between wings and propellers it appears that important delays in the onset of adverse compressibility effects should occur as the blade width is increased. Power limitations of the dynamometer prevented the attainment of sufficient data to substantiate this trend and further investigation is needed.

CONCLUSIONS

Very high solidity two-blade propellers (blade activity factors of 179 and 265) designated the NACA 4-(3)(06.3)-06 and NACA 4-(3)(06.4)-09 propellers have been tested in the NACA 8-foot high-speed tunnel through a range of blade angle from 20° to 70° for free-stream Mach numbers from 0.165 to 0.725. The results of these tests and comparisons with results from previous tests of the NACA 4-308-03 and NACA 4-308-045 propellers indicated the following conclusions:

1. The 0.06- and 0.09-solidity blades, although producing efficiencies of the order of 90 percent, were found to be less efficient than blades of conventional solidity.

2. The variation in average blade lift coefficient with solidity at a constant blade angle and advance-diameter ratio through the speed range of these tests was found to be analogous to the variation in wing lift coefficient with aspect ratio, indicating that high-solidity blades may be desirable for use at very high speeds. Because of power limitations of the test equipment conclusive evidence of the possible favorable effects of increased blade solidity at high speeds was not obtained. Further tests are desirable.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va.

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1. Stack, John, Draley, Eugene C., Delano, James B., and Feldman, Lewis: Investigation of Two-Blade Propellers at High Forward Speeds in the NACA 8-Foot High-Speed Tunnel. I - Effects of Compressibility. NACA 4-308-03 Blade. NACA ACR No. 4A10, 1944.

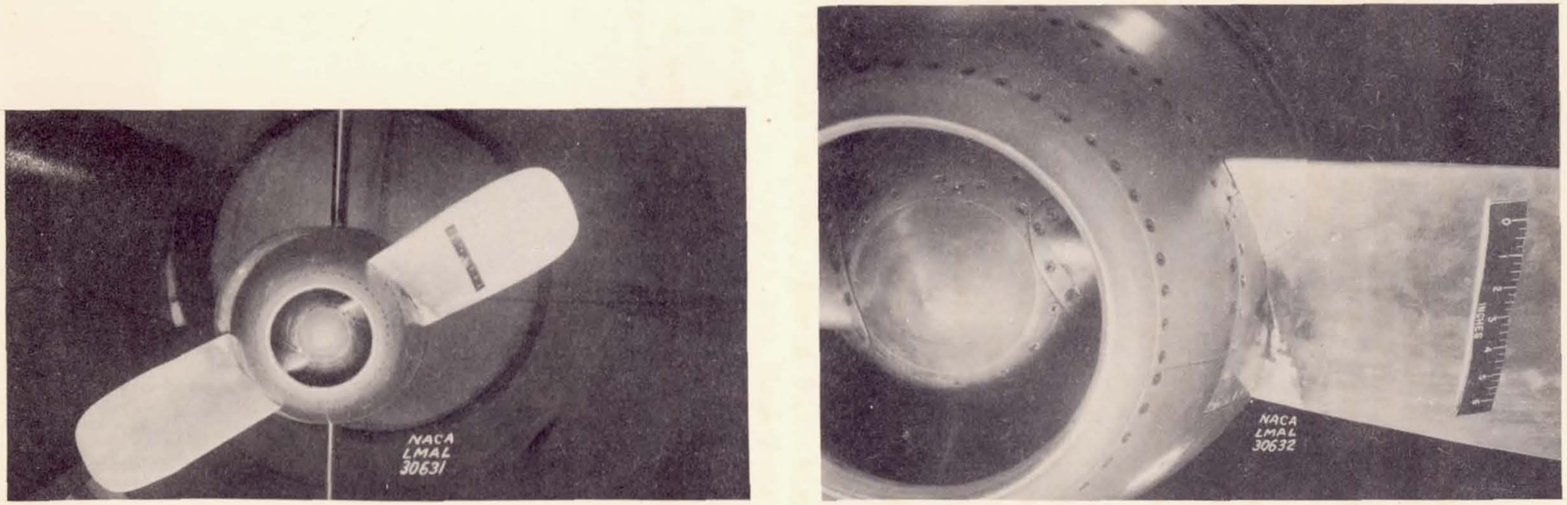
2. Stack, John, Draley, Eugene C., Delano, James B., and Feldman, Lewis: Investigation of Two-Blade Propellers at High Forward Speeds in the NACA 8-Foot High-Speed Tunnel. II - Effects of Compressibility and Solidity. NACA 4-308-045 Blade. NACA ACR No. 4B16, 1944.

3. Delano, James B.: Investigation of Two-Blade Propellers at High Forward Speeds in the NACA 8-Foot High-Speed Tunnel. III - Effects of Camber and Compressibility. NACA 4-(5)(08)-03 and NACA 4-(10)(08)-03 Blades. NACA ACR No. L5F15, 1945.

4. Betz, Albert: The Theory of Contra-Vanes Applied to the Propeller NACA TM No. 909, 1939.

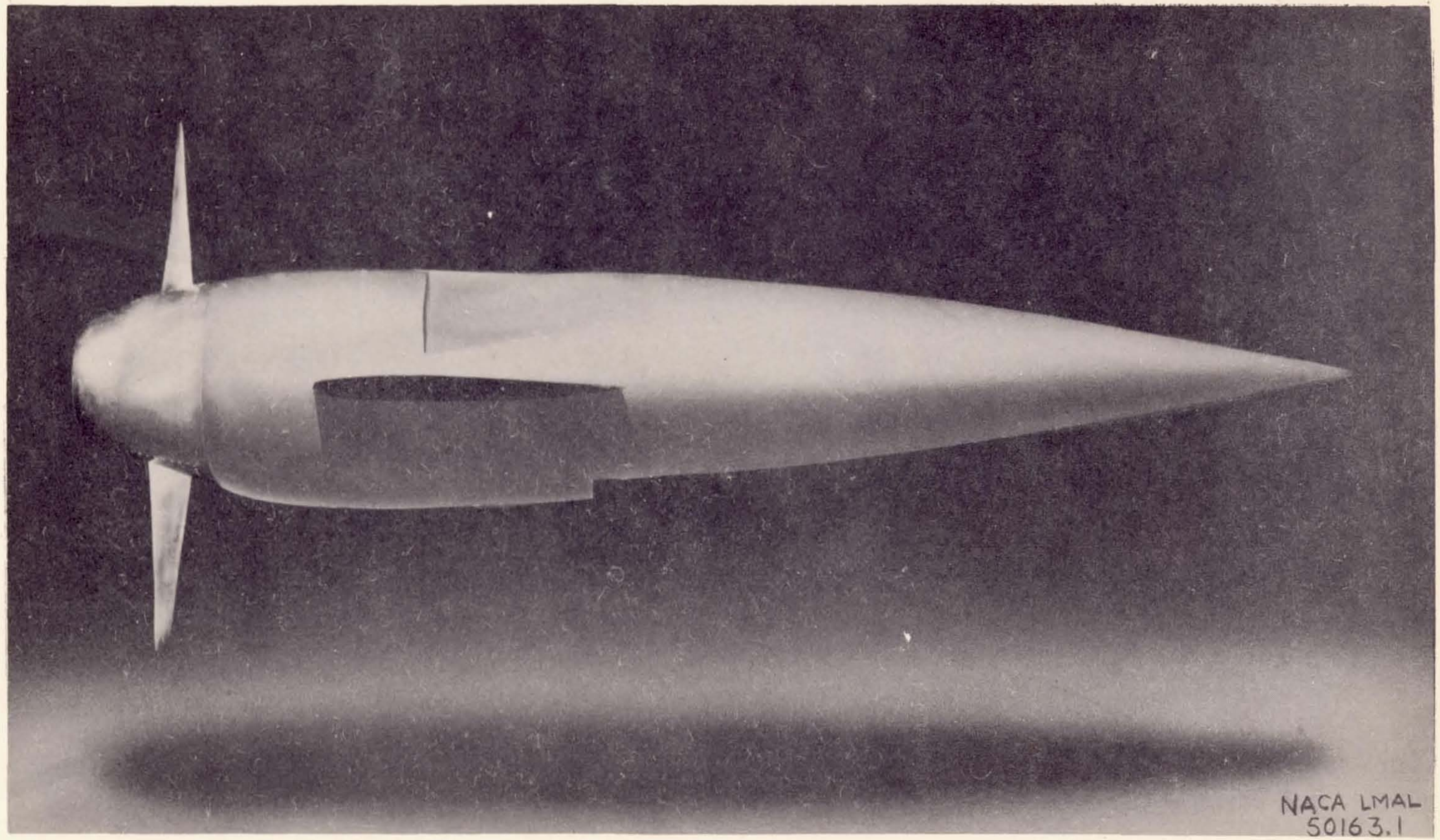
5. Biermann, David, and Hartman, Edwin P.: Wind-Tunnel Tests of Four- and Six-Blade Single- and Dual-Rotating Tractor Propellers. NACA Rep. No. 747, 1942.

6. Feldman, L.: A New Method of Propeller Analysis. A.D.R. Rep. T-16, Bur. Aero., 1945.



(a) NACA 4-(3)(06.4)-09 propeller. (b) Shank details for the NACA 4-(3)(06.4)-09 propeller.

Figure 1.- Propeller test setup.



(c) Test body.

Figure 1.- Concluded.

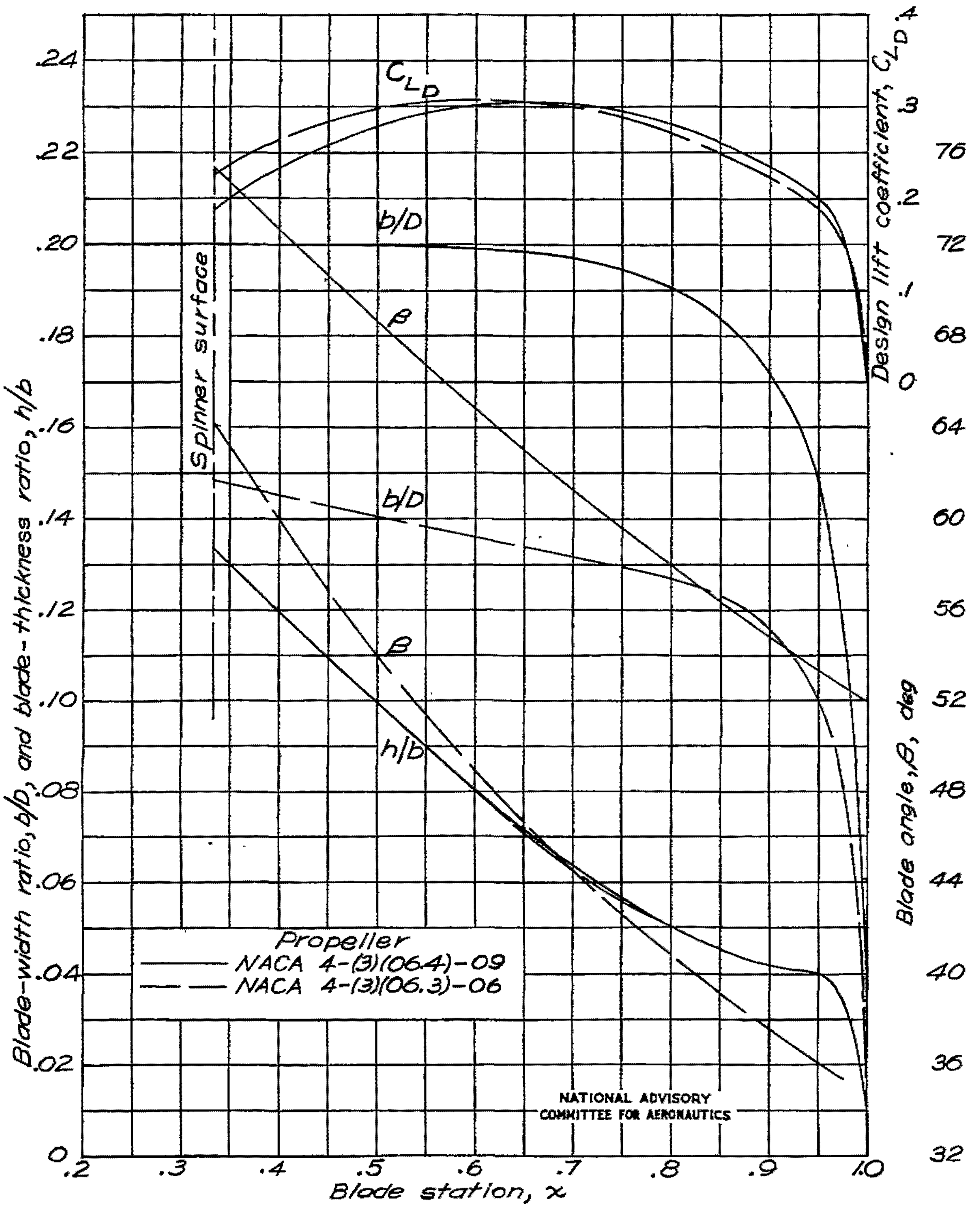
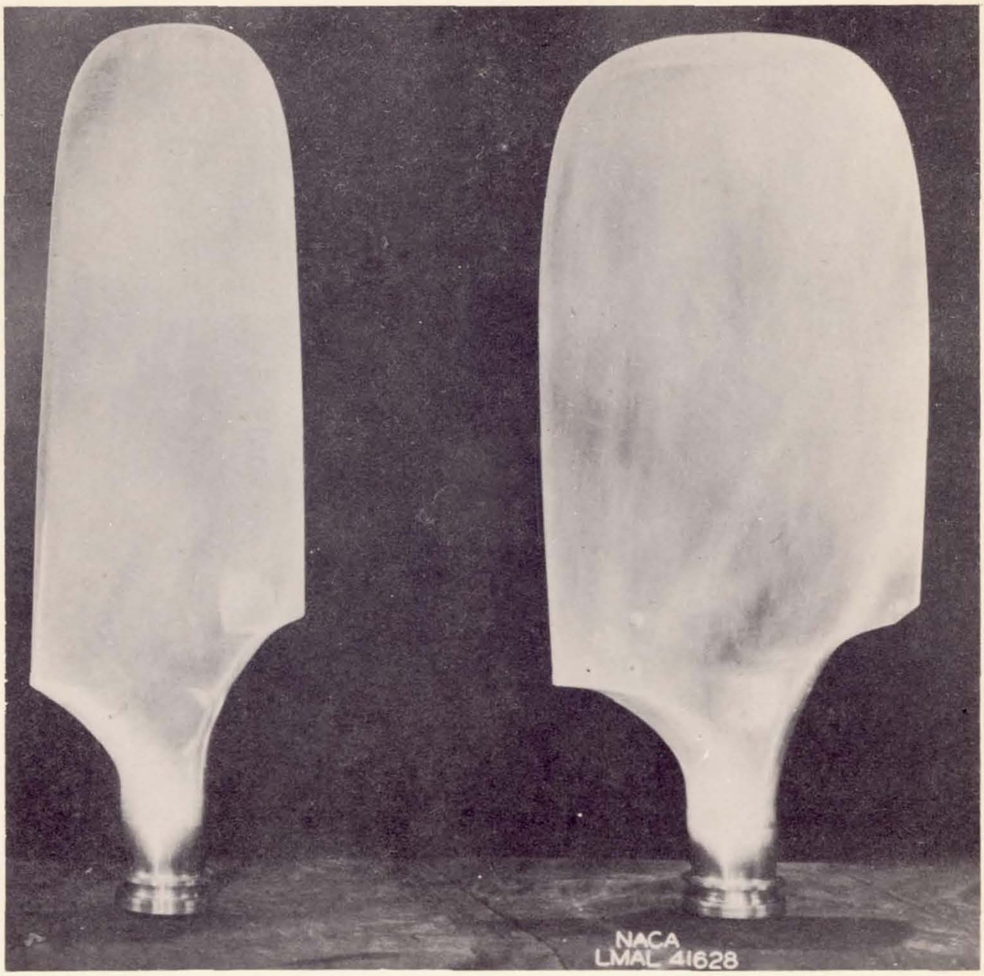
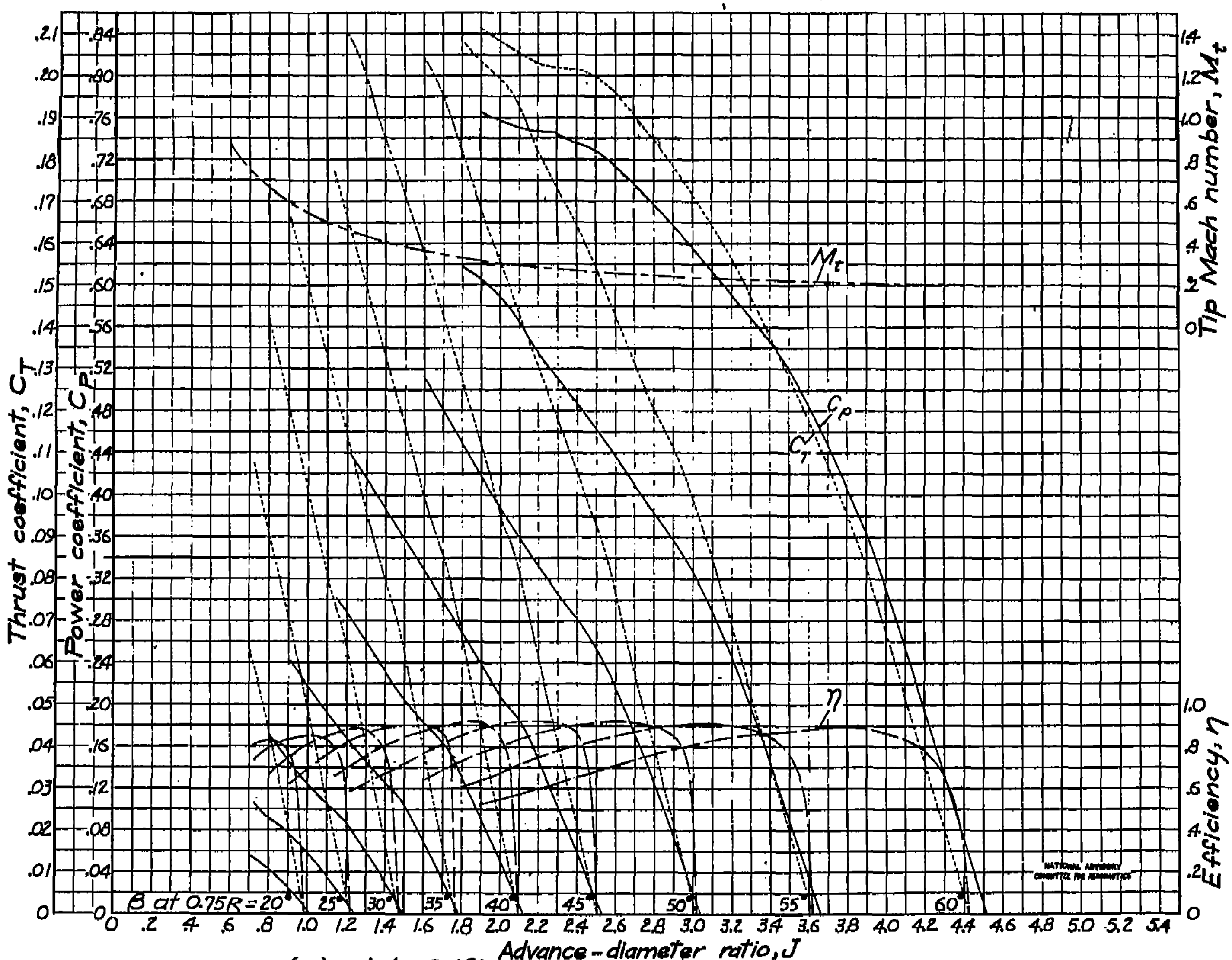


Figure 2.— Blade-form curves for propellers tested.



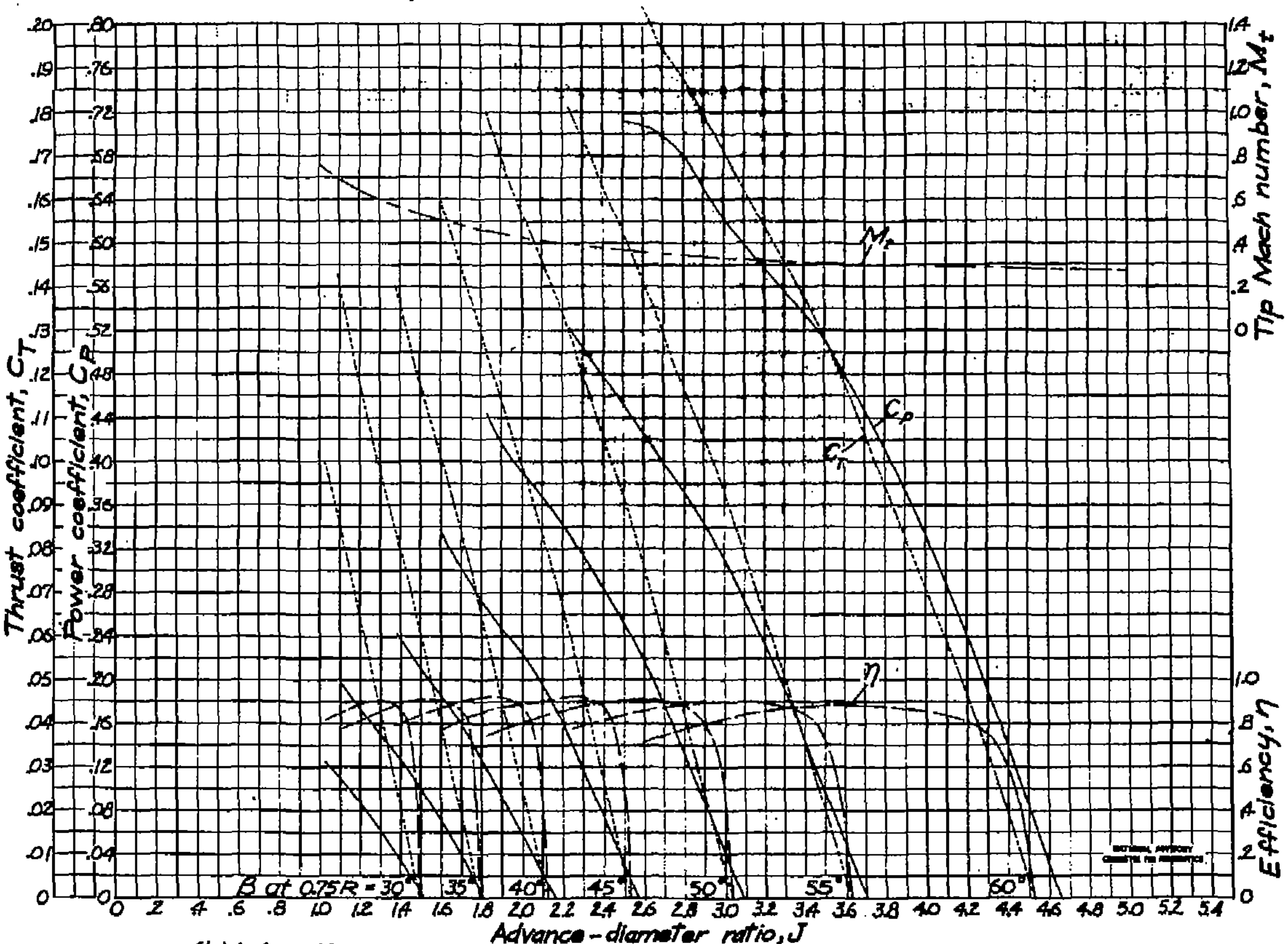
(a) NACA 4-(3)(06.3)-06 blade. (b) NACA 4-(3)(06.4)-09 blade.

Figure 3.- Test blades.



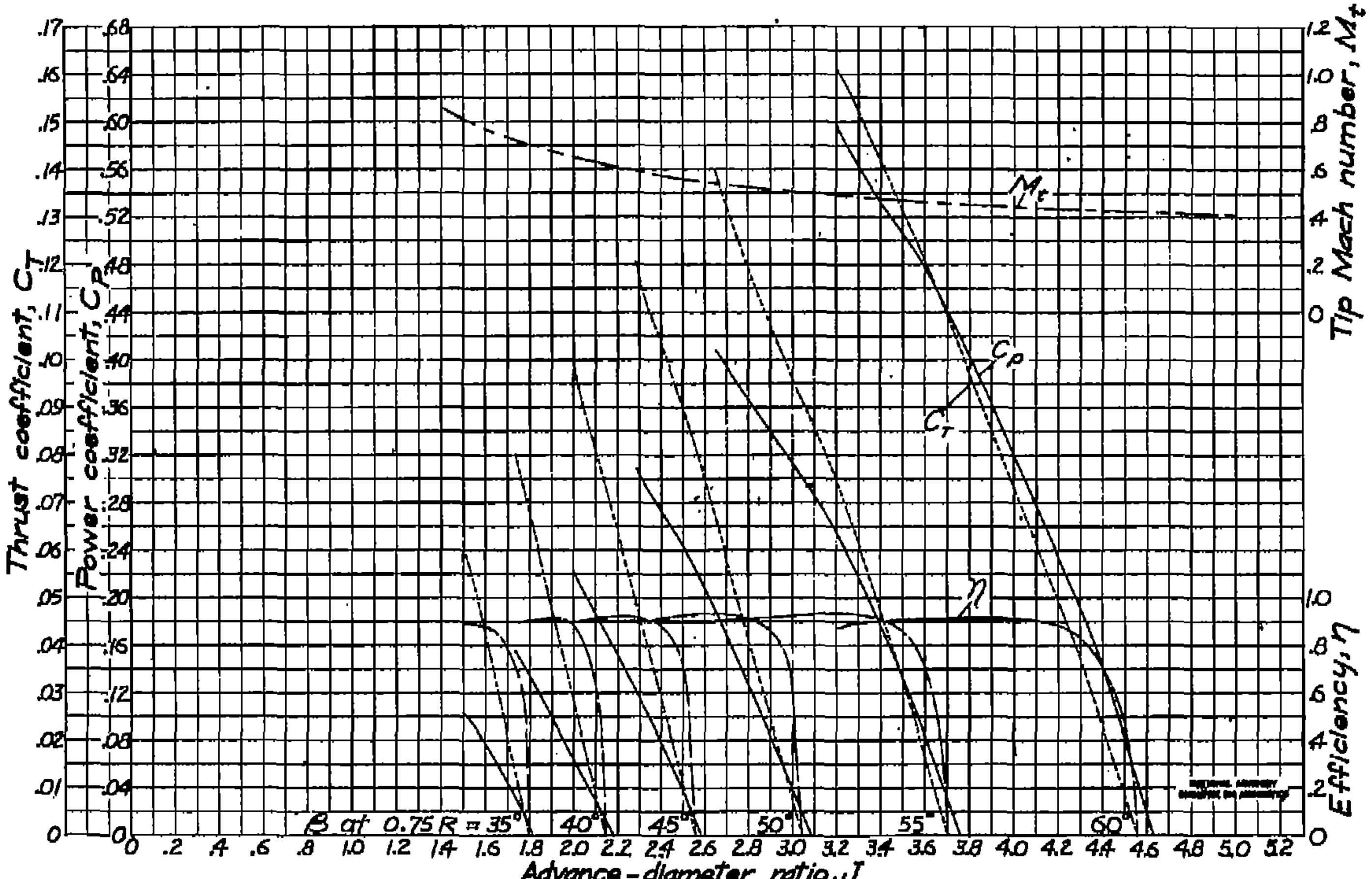
(a) $M = 0.165$.

Figure 4.- Characteristics for the NACA 4-(3)(063)-06 propeller.



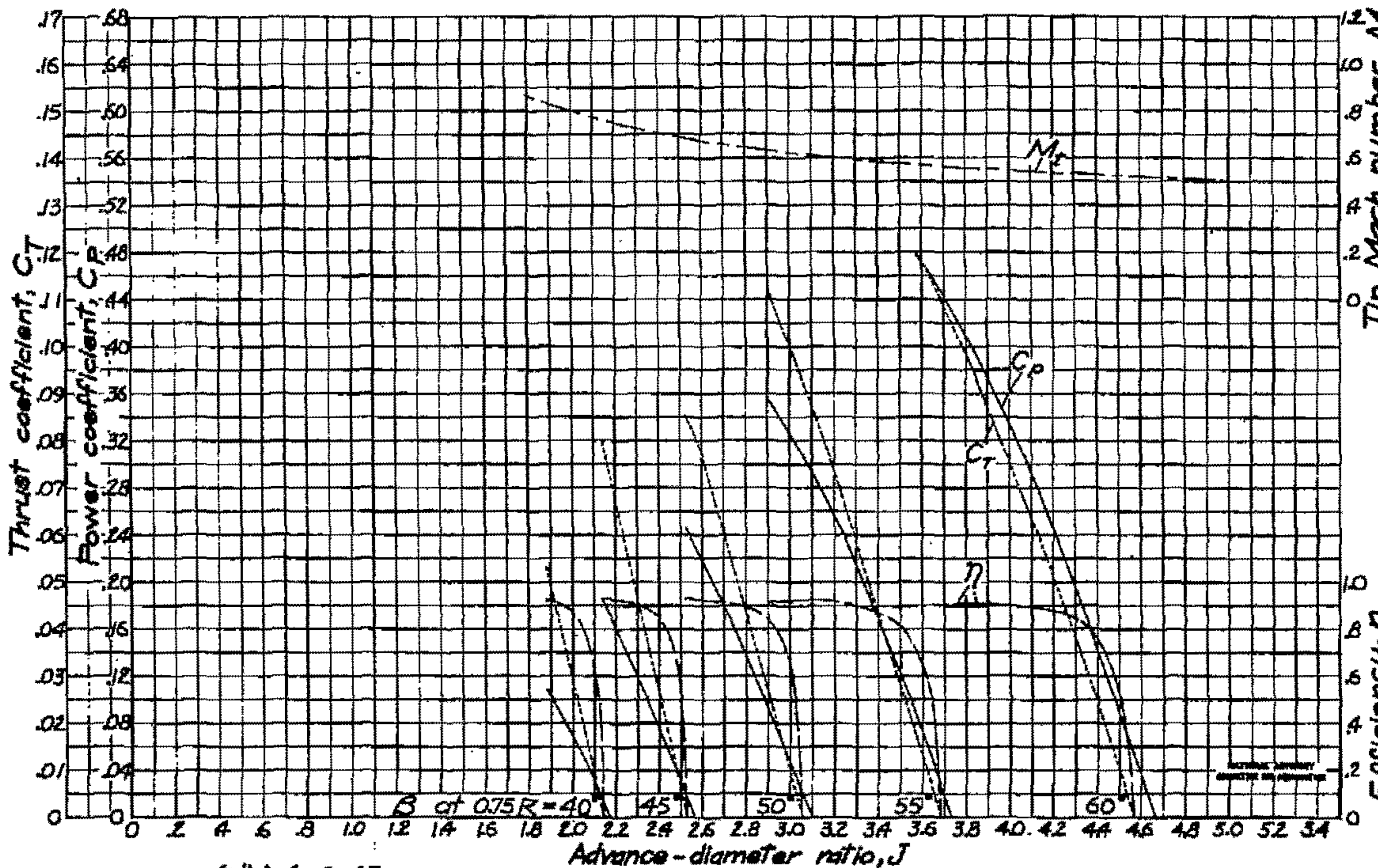
(b) M = 0.23.

Figure 4.-Continued. Characteristics for the NACA 4-(3)(06.3)-06 propeller.



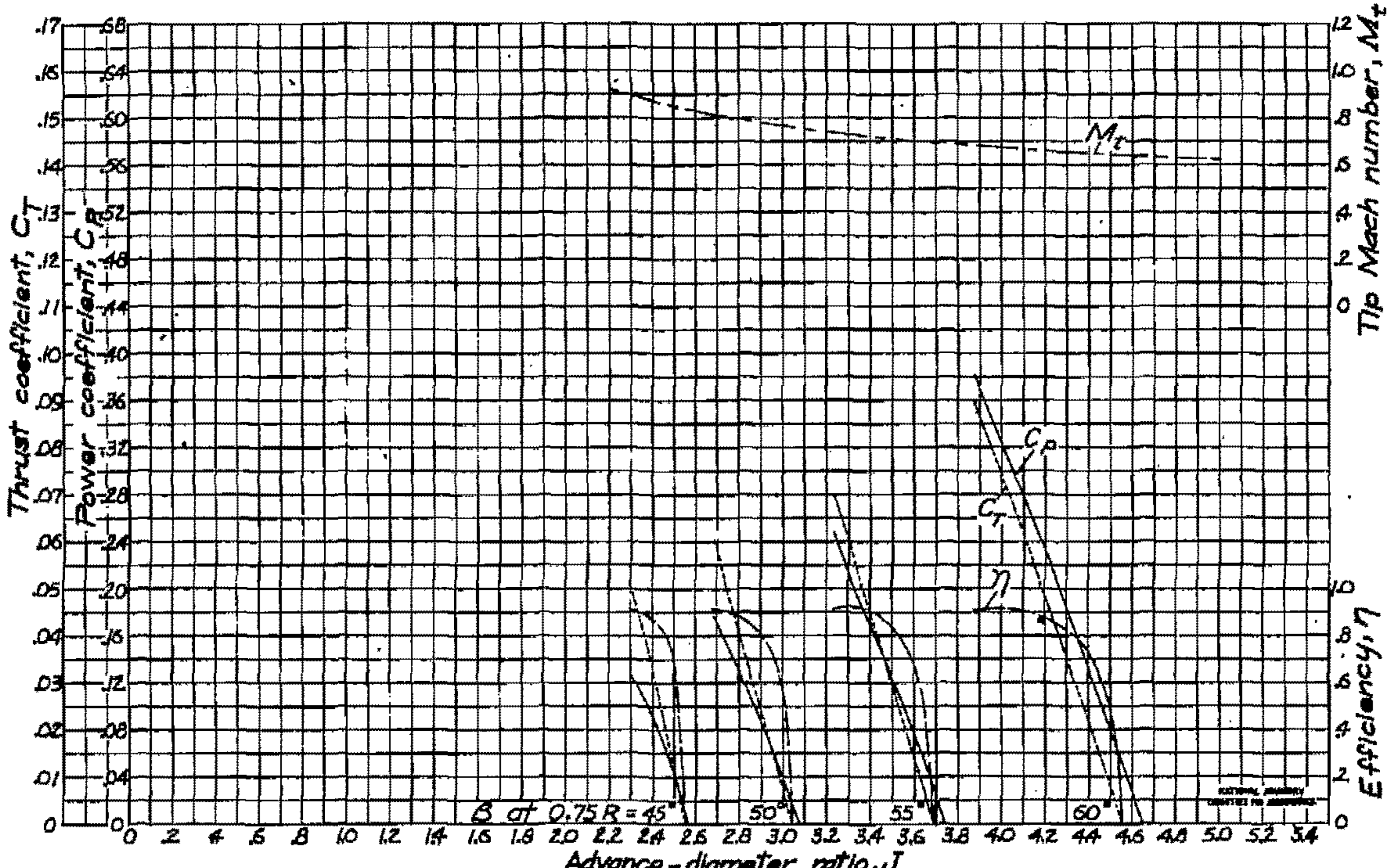
(c) M=0.35.

Figure 4.- Continued. Characteristics for the NACA 4-(3)(06.3)-06 propeller.



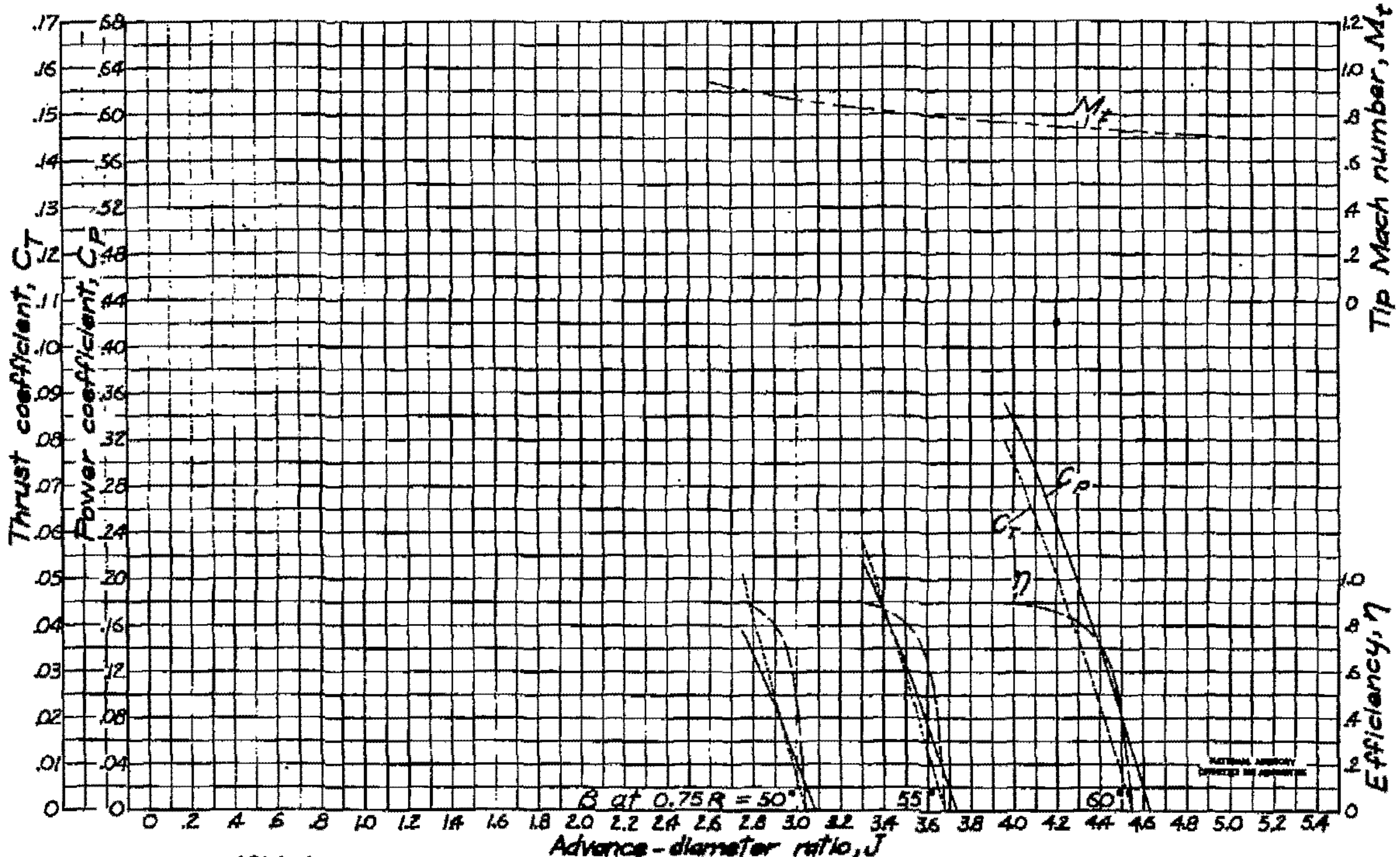
(d) $M = 0.43$.

Figure 4.- Continued. Characteristics for the NACA 4-(3)(06.3)-06 propeller.



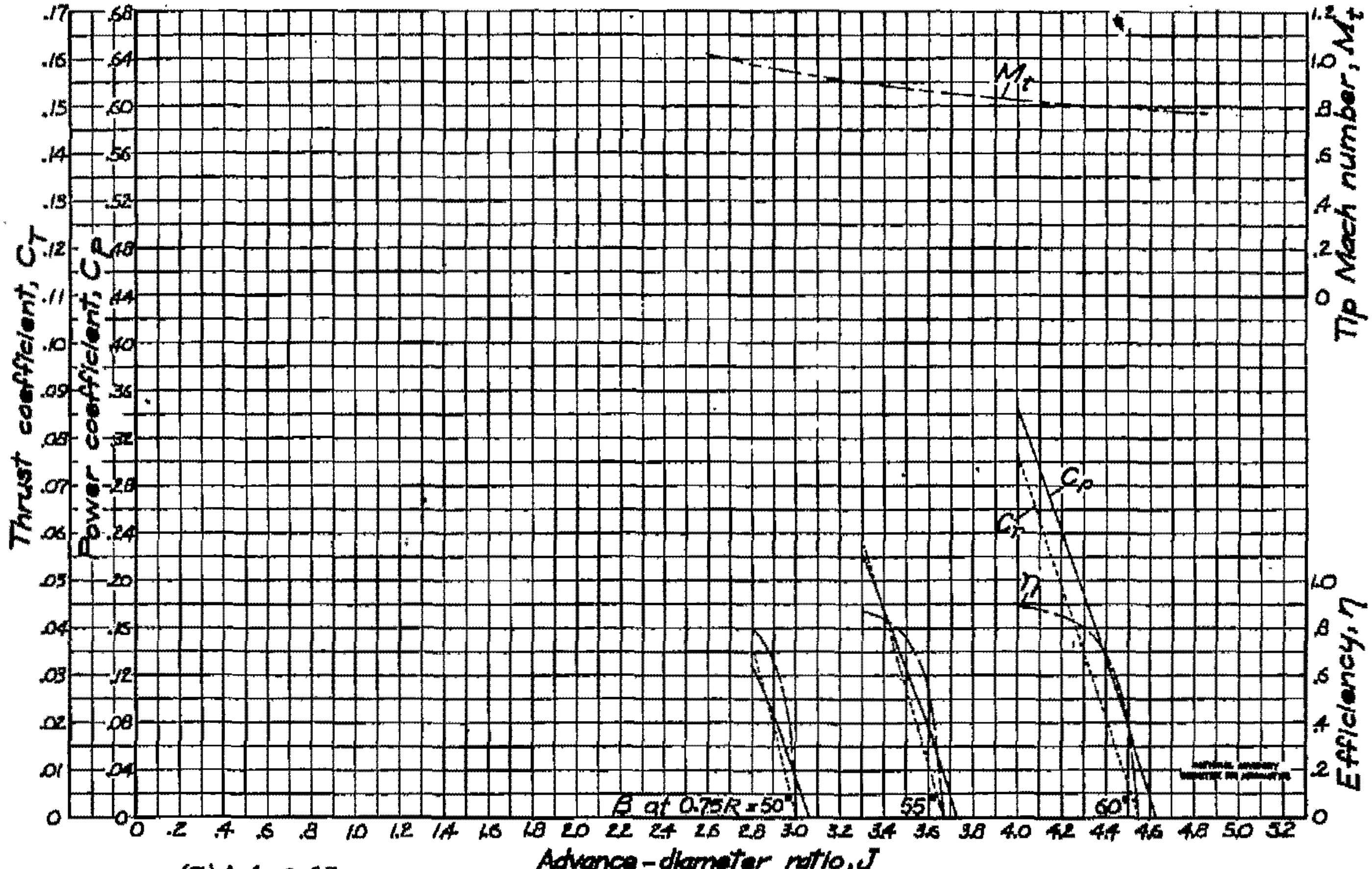
(e) $M = 0.53$.

Figure 4.-Continued. Characteristics for the NACA 4-(3)(063)-06 propeller.



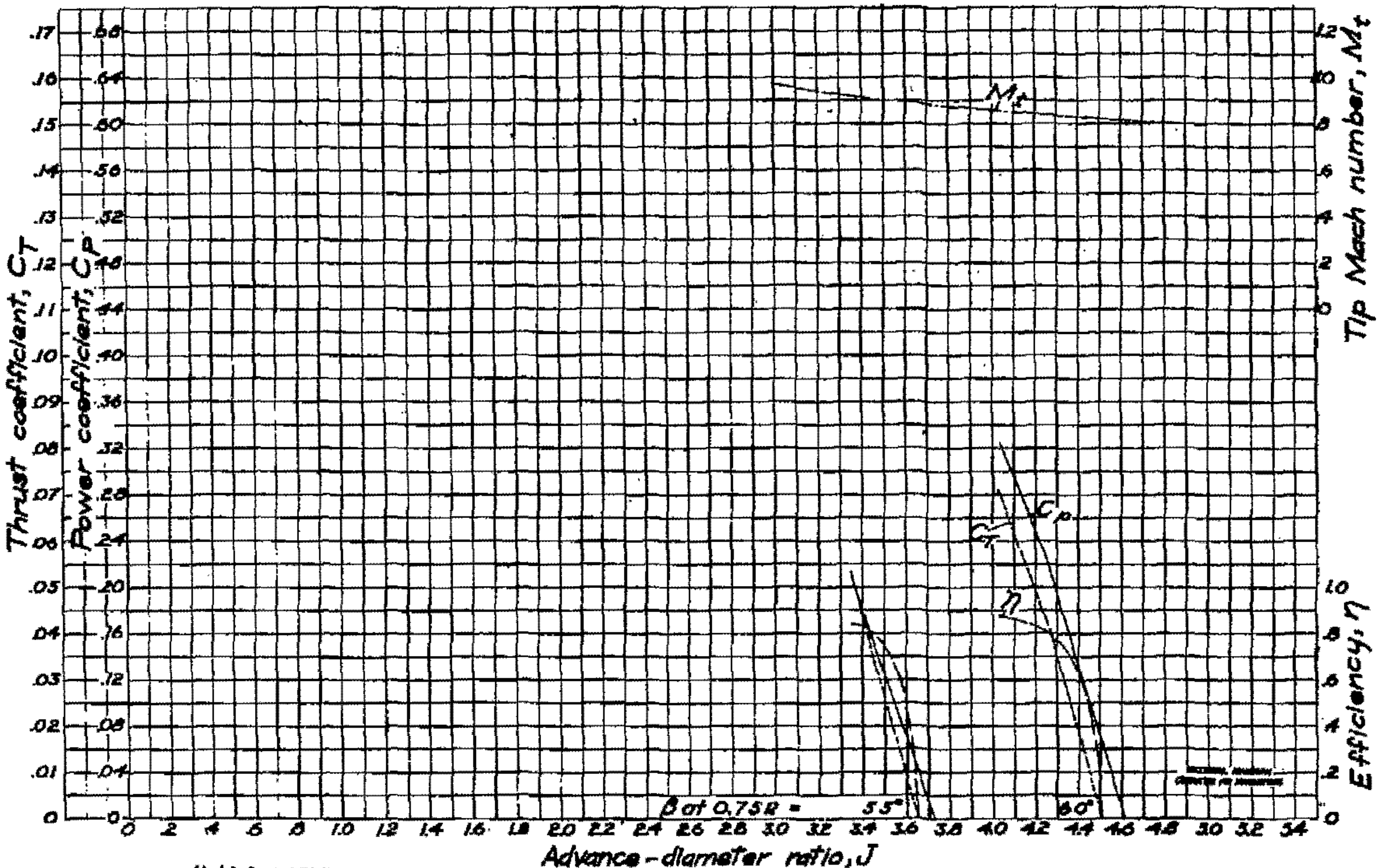
(f) M=0.60.

Figure 4.-Continued. Characteristics for the NACA 4-(3)(06.3)-06 propeller.



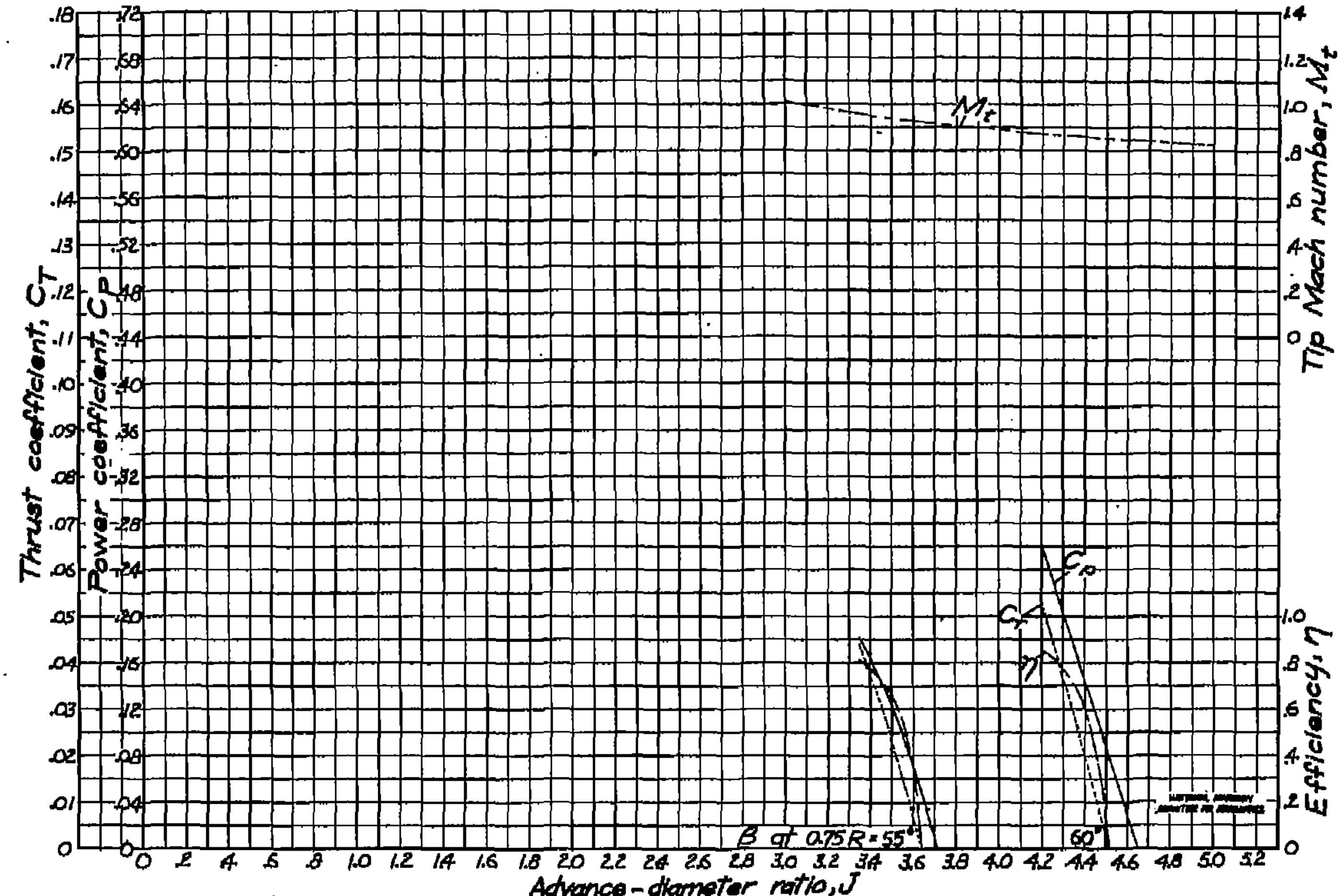
(g) M = 0.65.

Figure 4.- Continued. Characteristics for the NACA 4-(3)(06.3)-06 propeller.



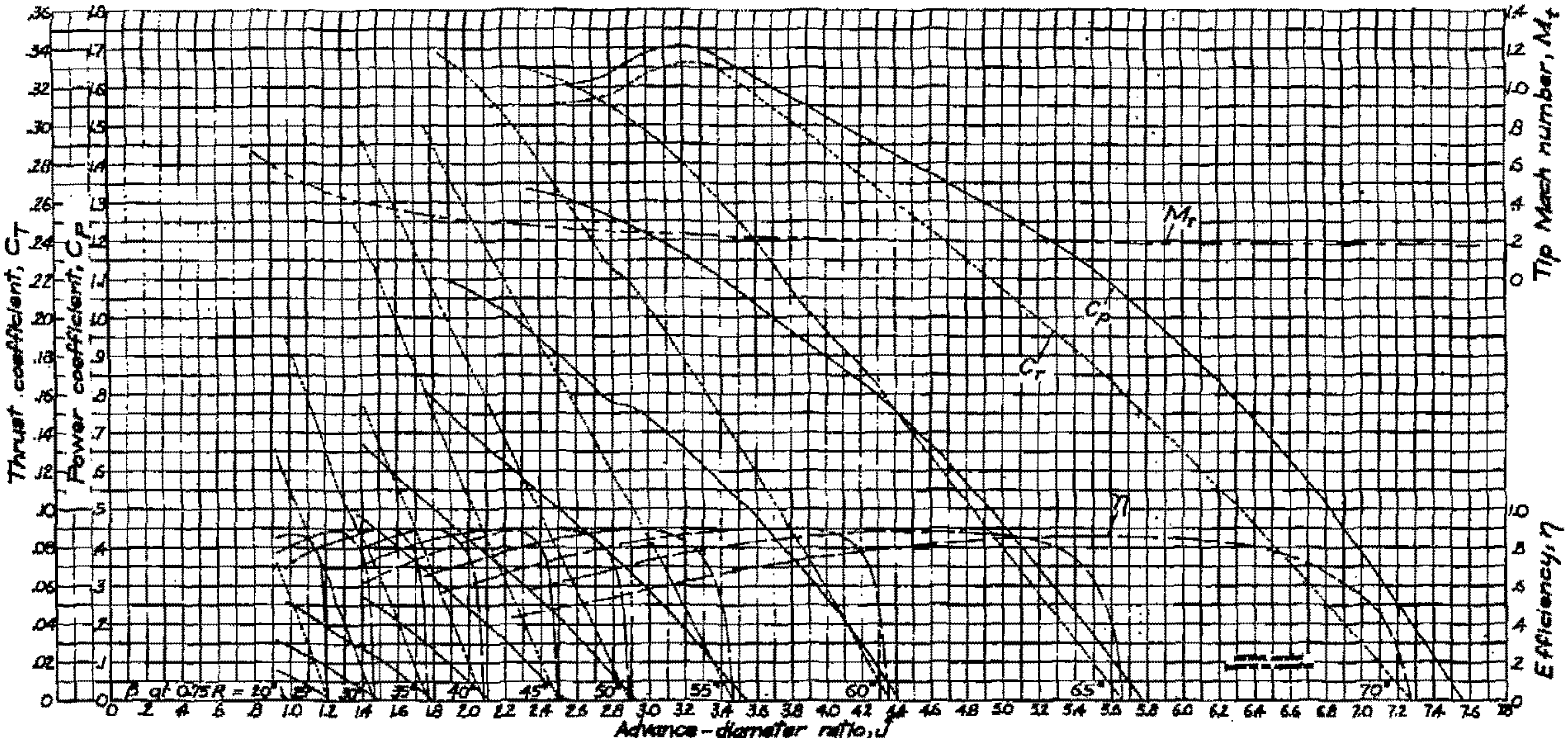
(h) M=0.675.

Figure 4 .- Continued. Characteristics for the NACA 4-(3)(06.3)-06 propeller.



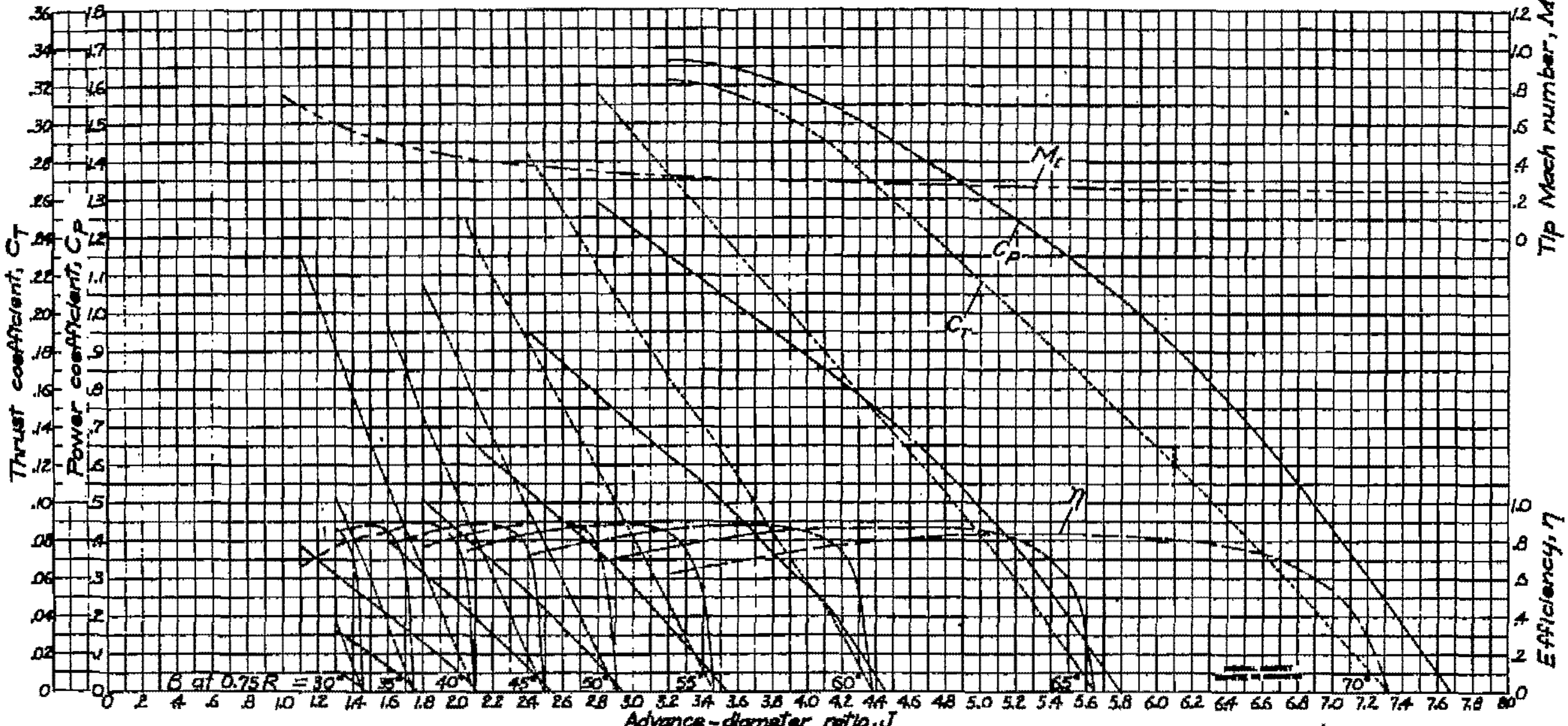
(i) M=0.700.

Figure 4.-Concluded. Characteristics for the NACA 4-(3)(063)-06 propeller.



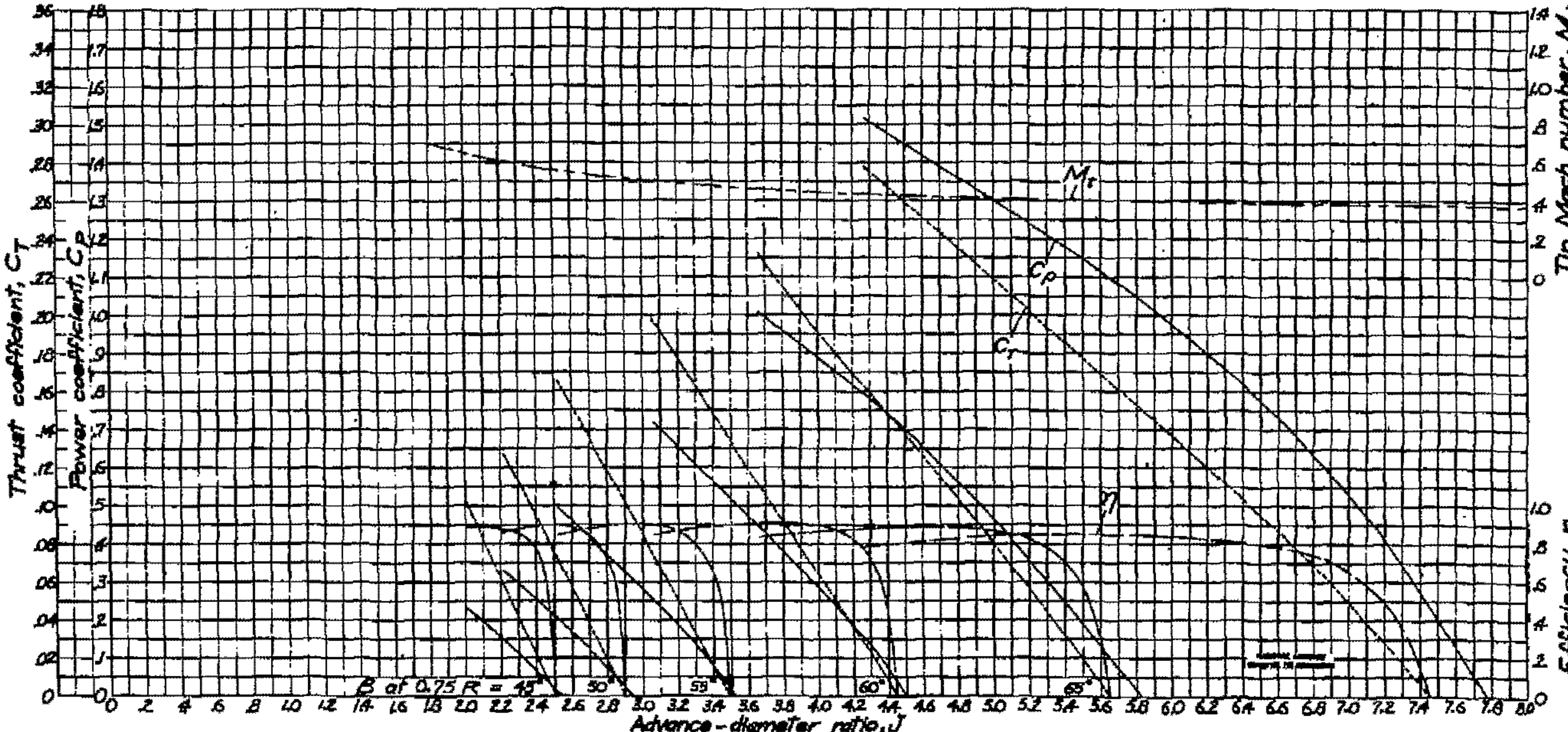
(a) $M = 0.165$.

Figure 5.- Characteristics for the NACA 4-(3)(064)-09 propeller.



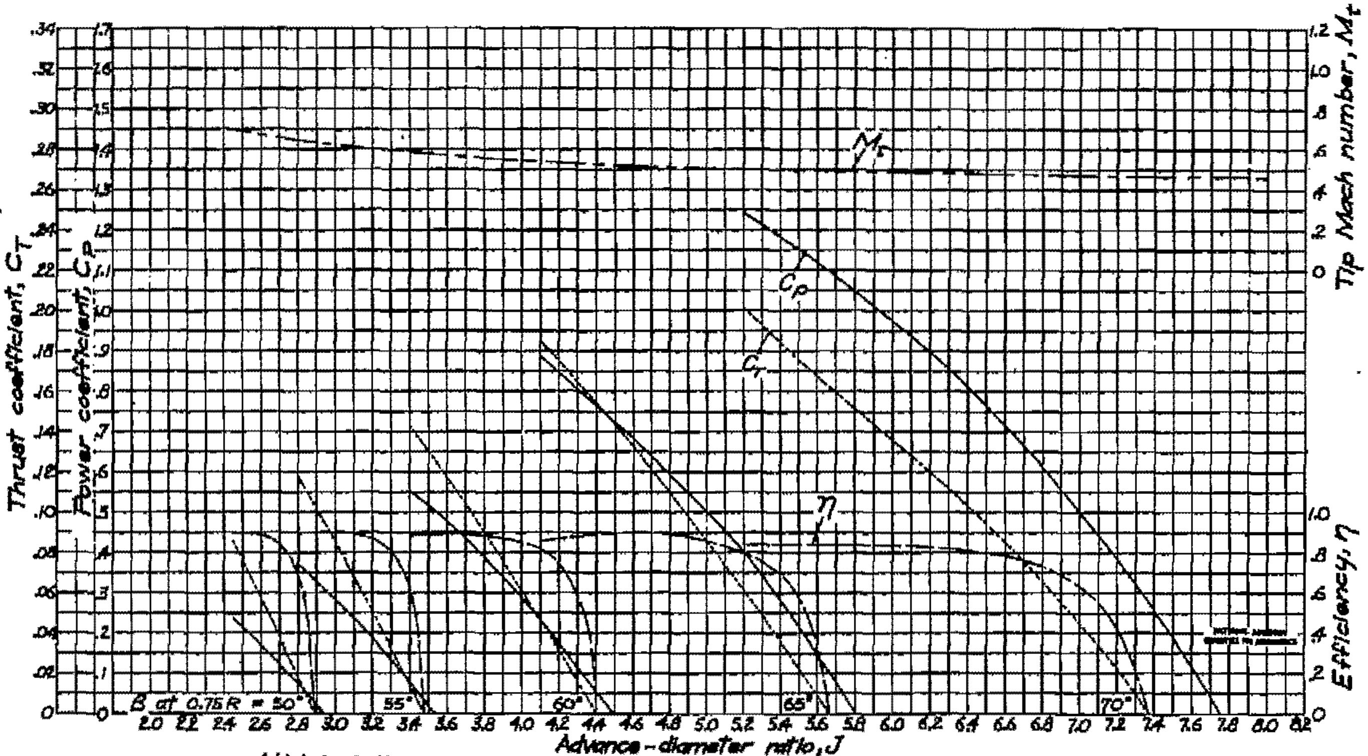
(b) M=0.23.

Figure 5.-Continued. Characteristics for the NACA 4-(3)(06.4)-09 propeller.



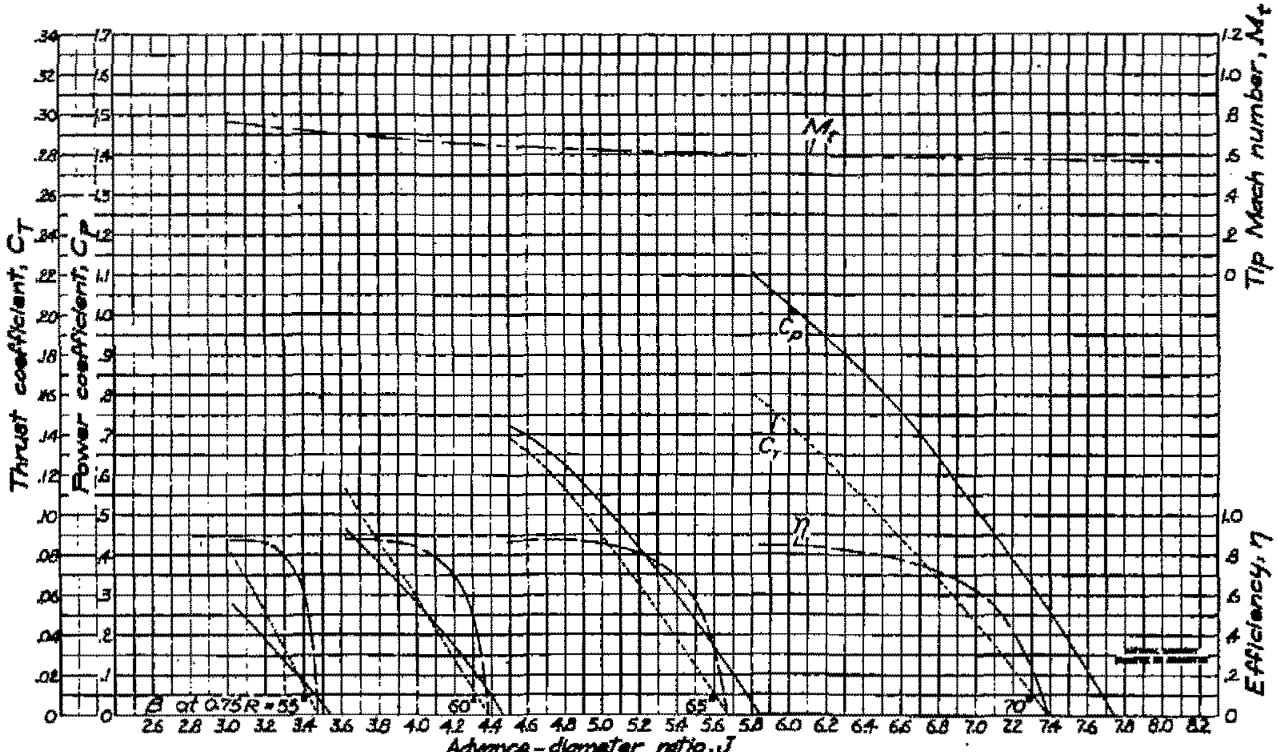
(c) M=0.35.

Figure 5.-Continued. Characteristics for the NACA 4-(3)(064)-09 propeller.



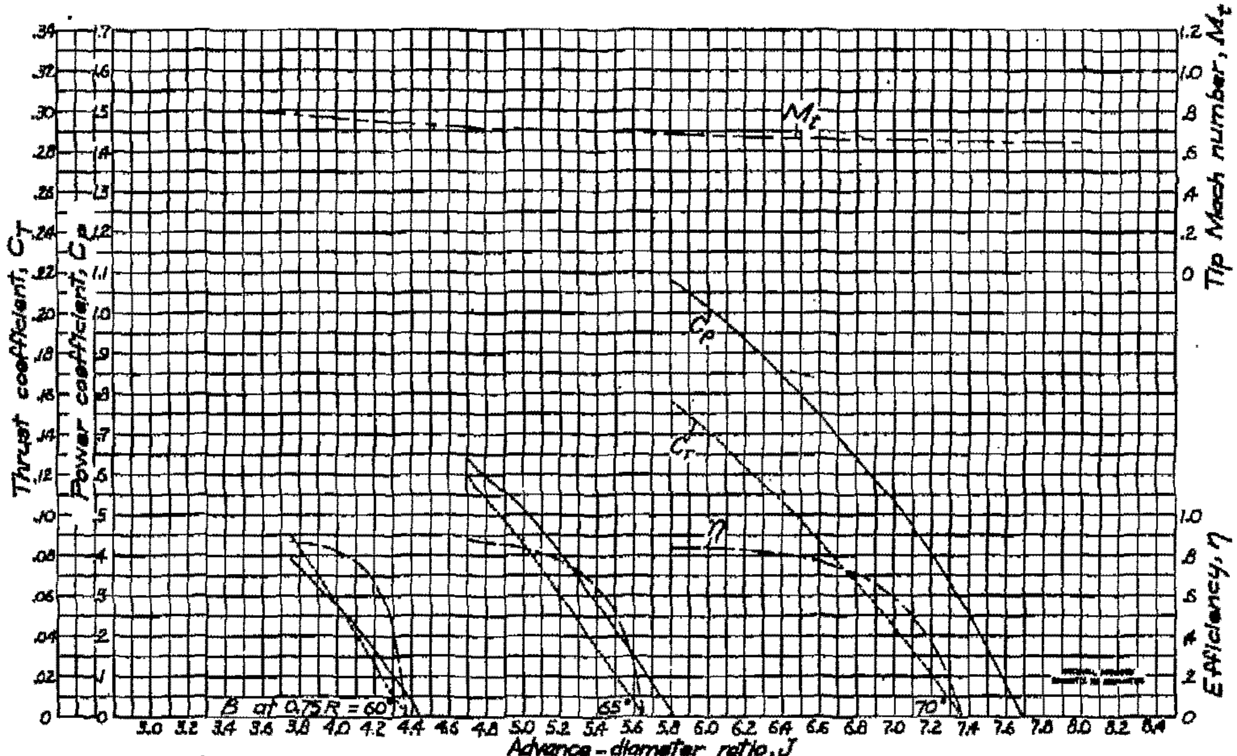
(d) $M = 0.43$.

Figure 5.-Continued. Characteristics for the NACA 4-(3)(064)-09 propeller.



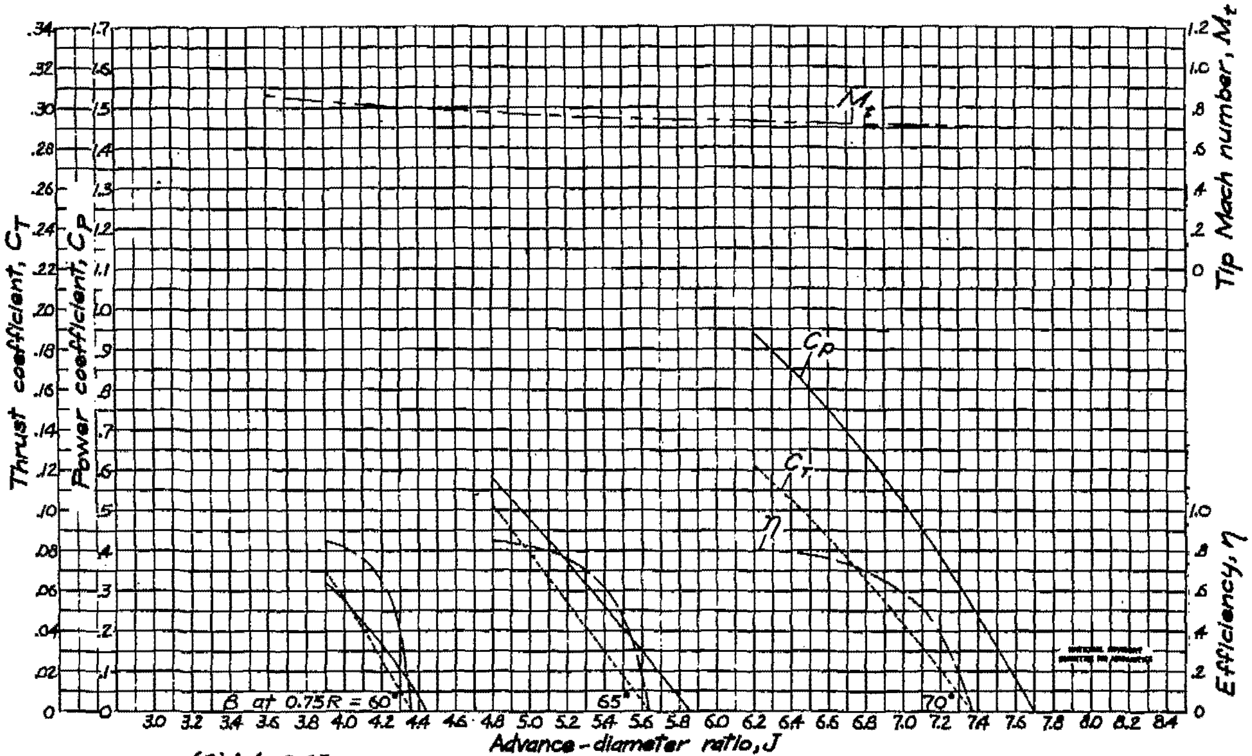
(e) M=0.53.

Figure 5.-Continued. Characteristics for the NACA 4-(3)(064)-09 propeller.



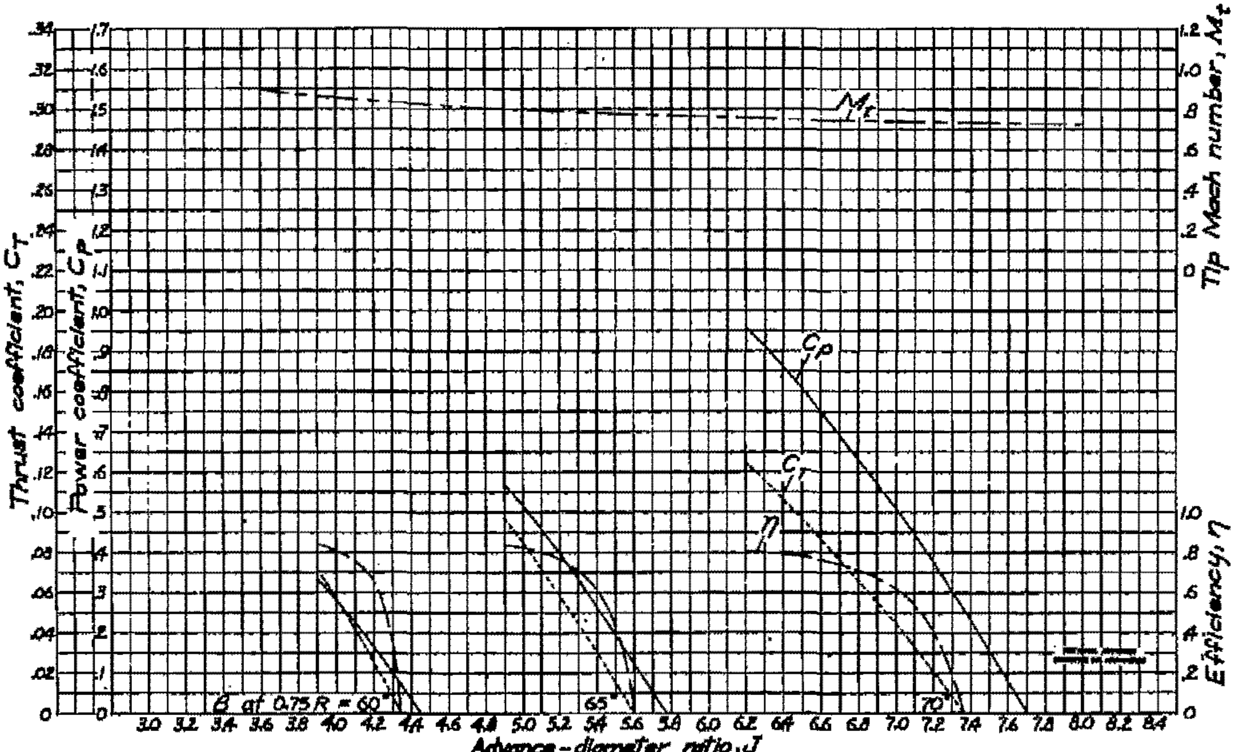
(f) M = 0.60.

Figure 5.-Continued. Characteristics for the NACA 4(3)(064)-09 propeller.



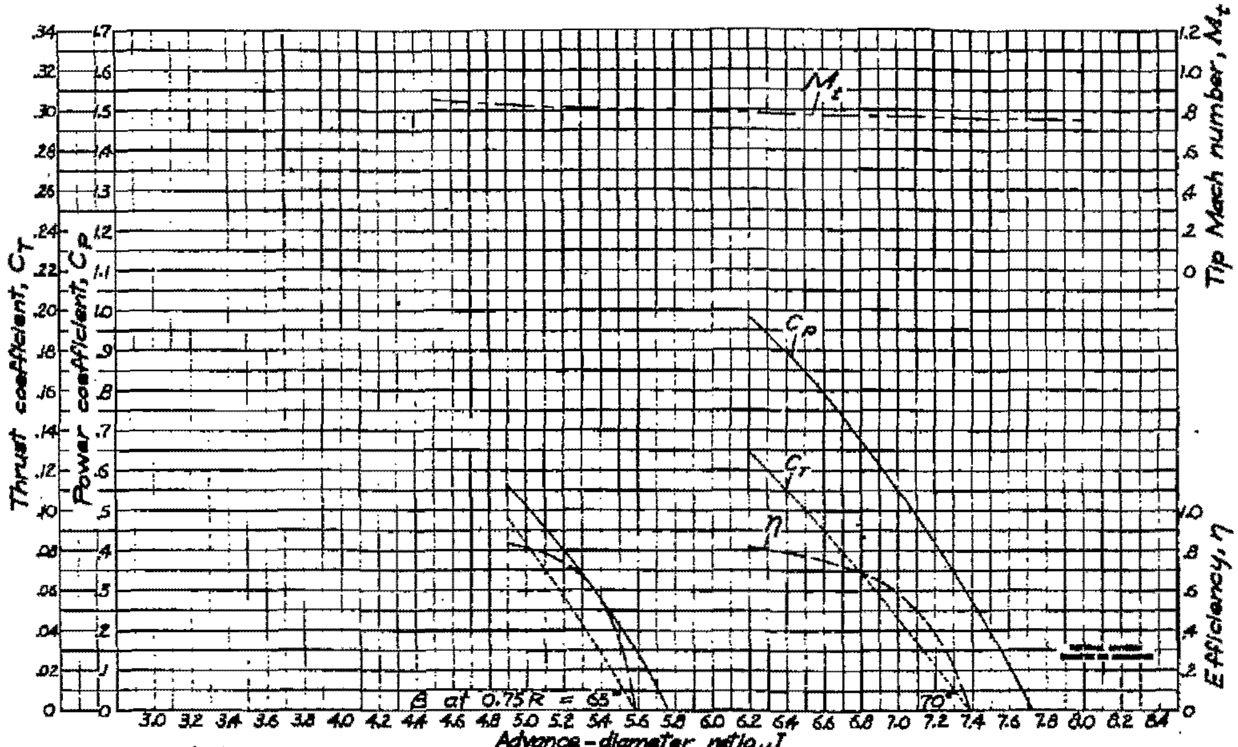
(g) $M = 0.65$.

Figure 5.-Continued. Characteristics for the NACA 4-(3)(06.4)-09 propeller.



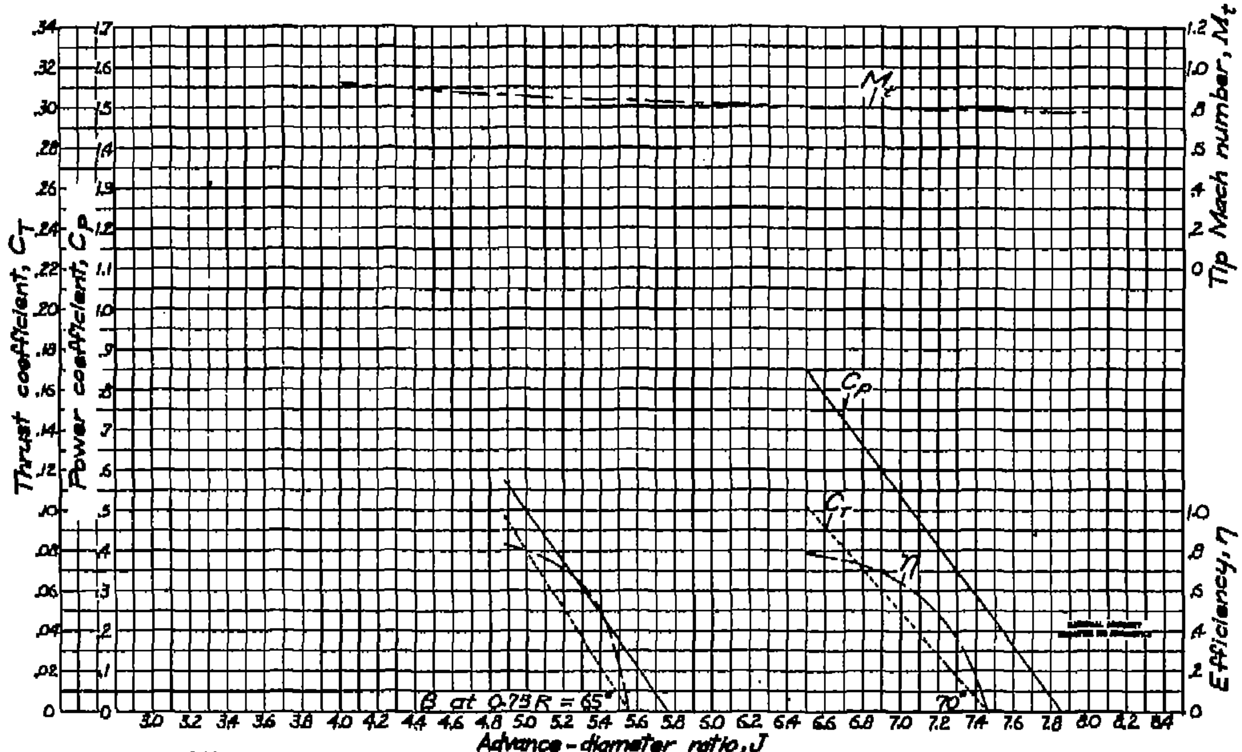
(h) M = 0.675.

Figure 5.- Continued. Characteristics for the NACA 4-(3)(064)-09 propeller.



(l) M=0.700.

Figure 5.-Continued. Characteristics for the NACA 4-(3)(064)-09 propeller.



(J) M = 0.725.

Figure 5.-Concluded. Characteristics for the NACA 4(3)(06.4)-09 propeller.

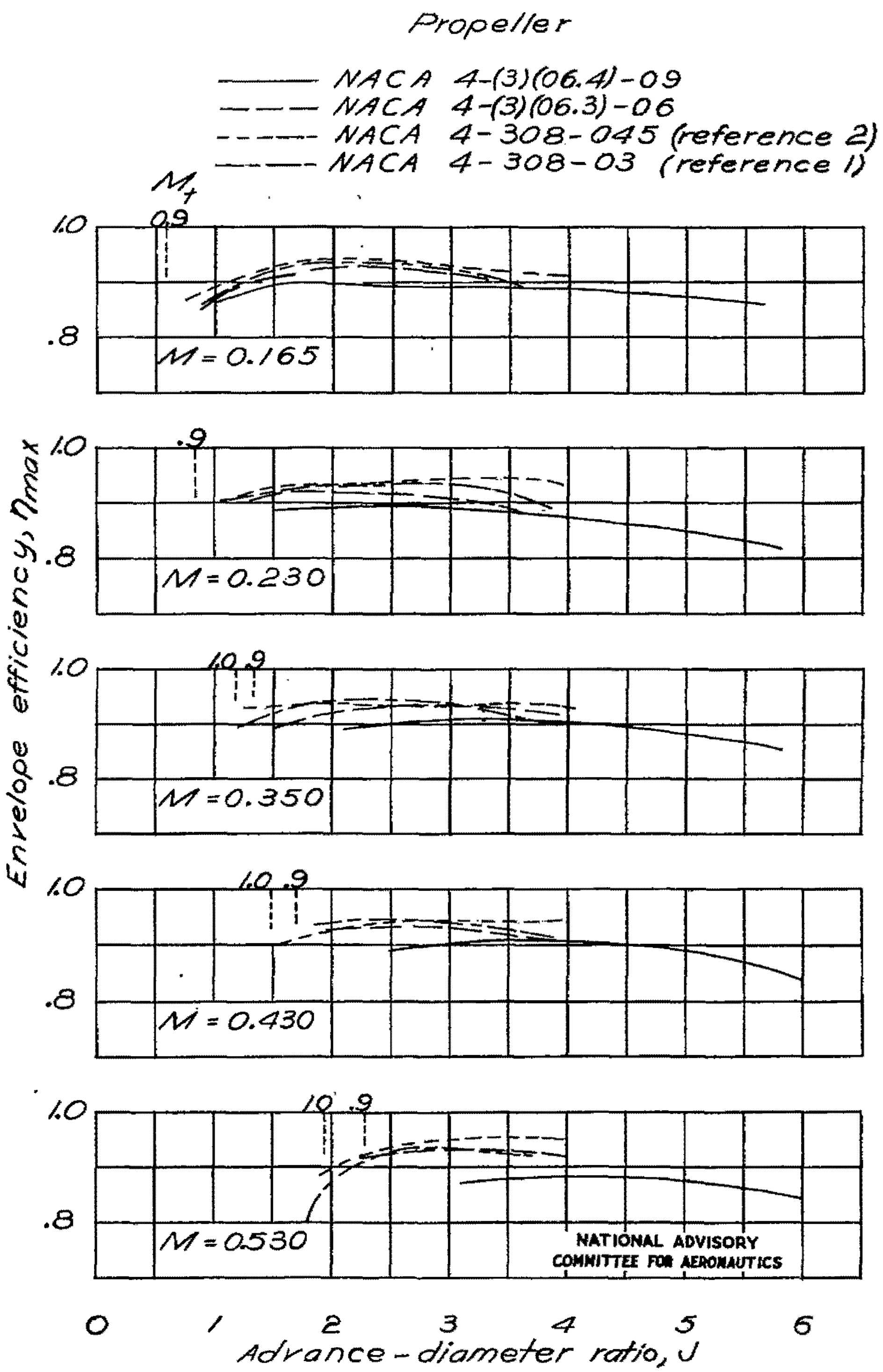


Figure 6.- Effect of compressibility on envelope efficiency.

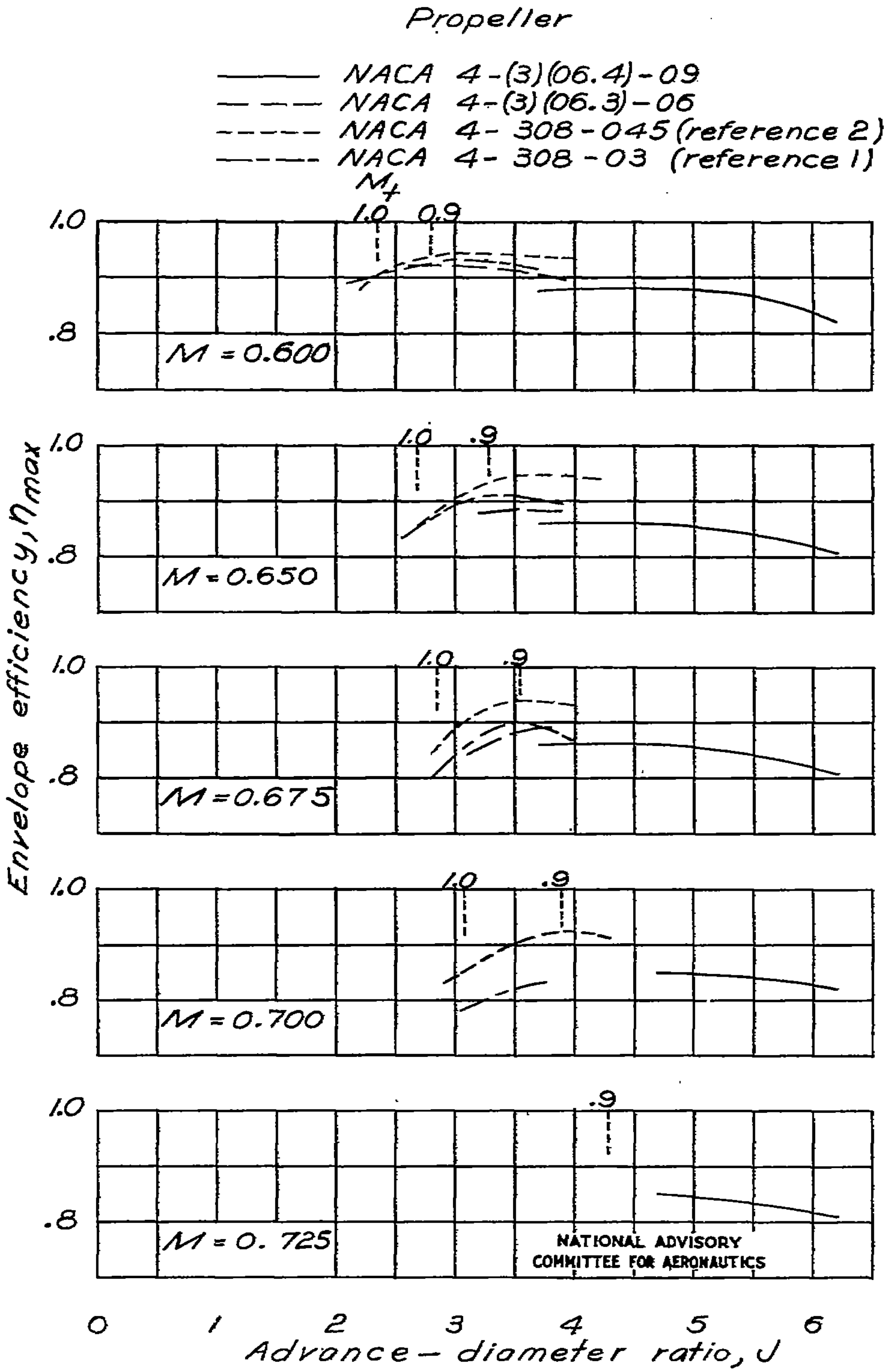


Figure 6 .— Concluded.

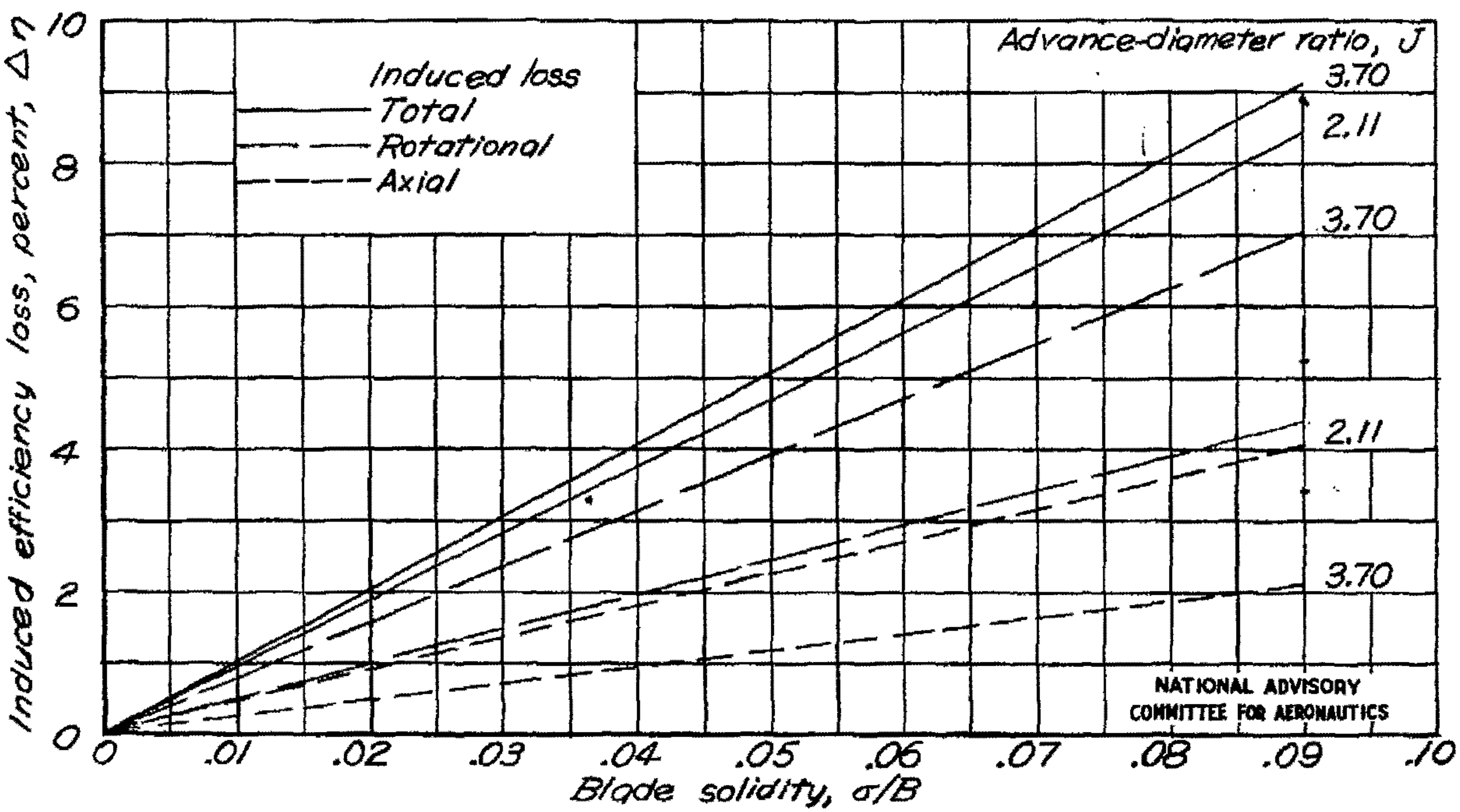
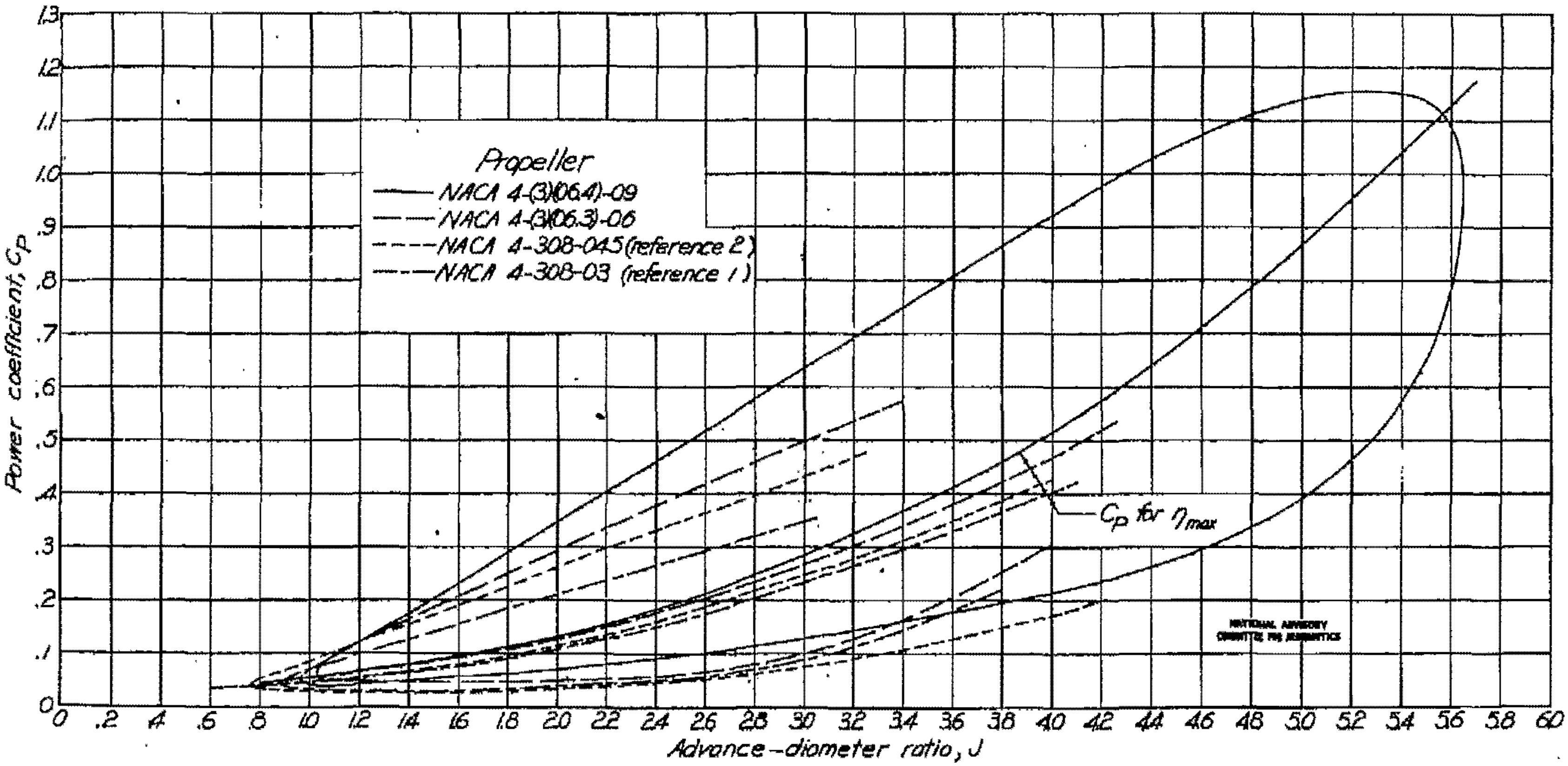
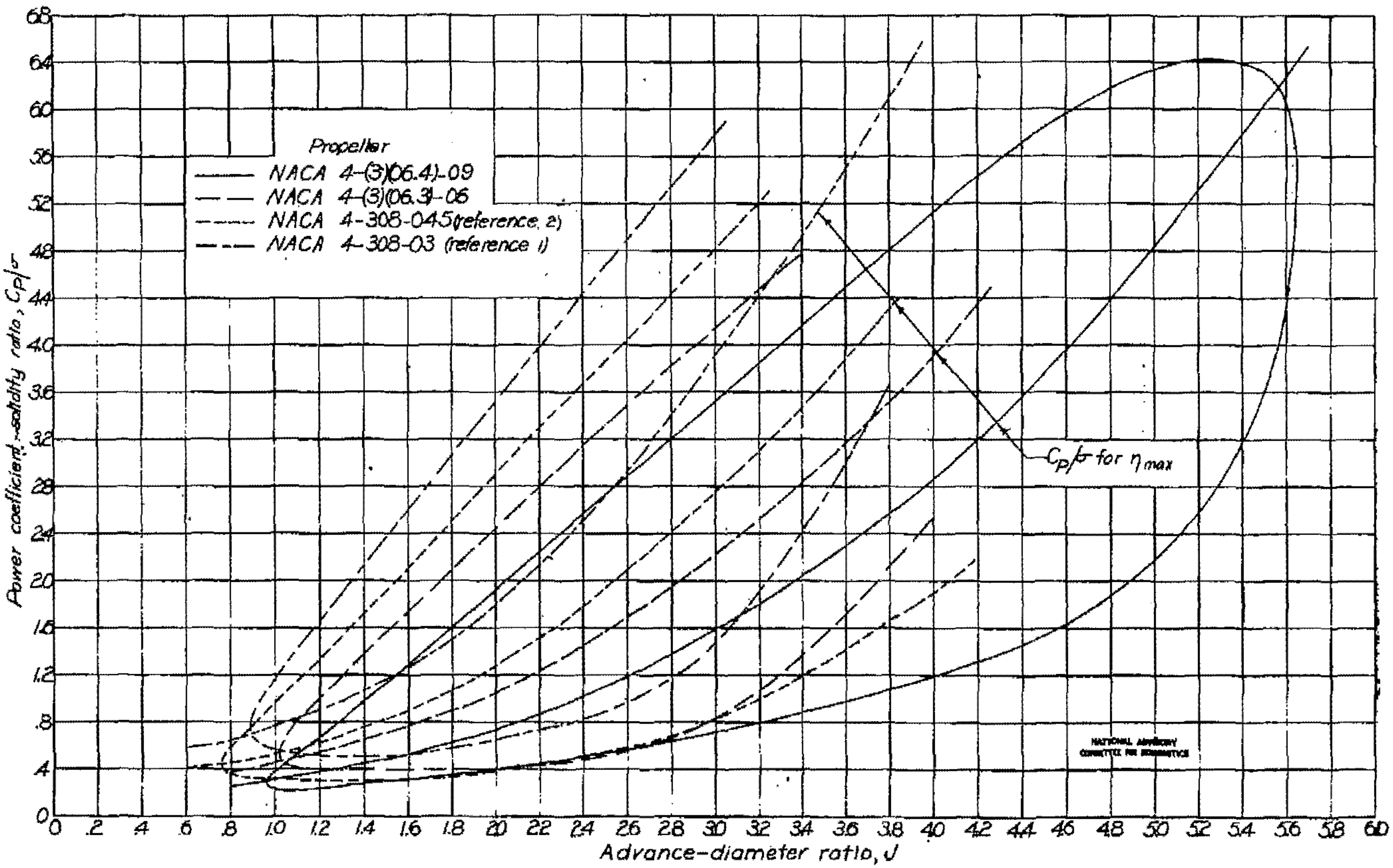


Figure 7 .– Induced losses for two-blade propellers with optimum loading.



(a) Power coefficient.

Figure 8.– Range of power coefficient and power coefficient-solidity ratio for efficiencies above 86 percent. M-0.165.



(b) Power coefficient-solidity ratio.

Figure 8.- Concluded.

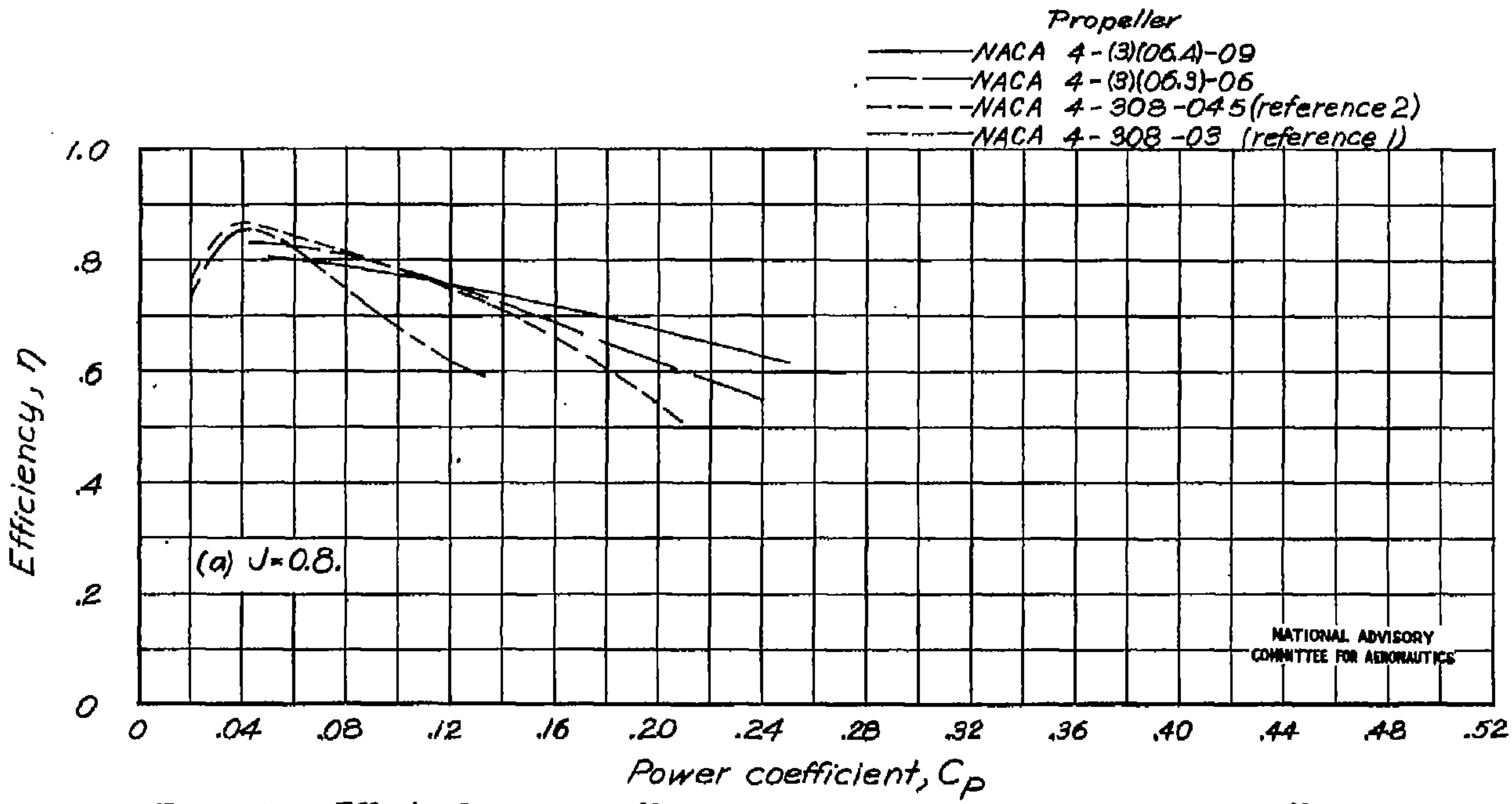


Figure 9.– Effect of power coefficient and advance-diameter ratio on efficiency. $M = 0.165$.

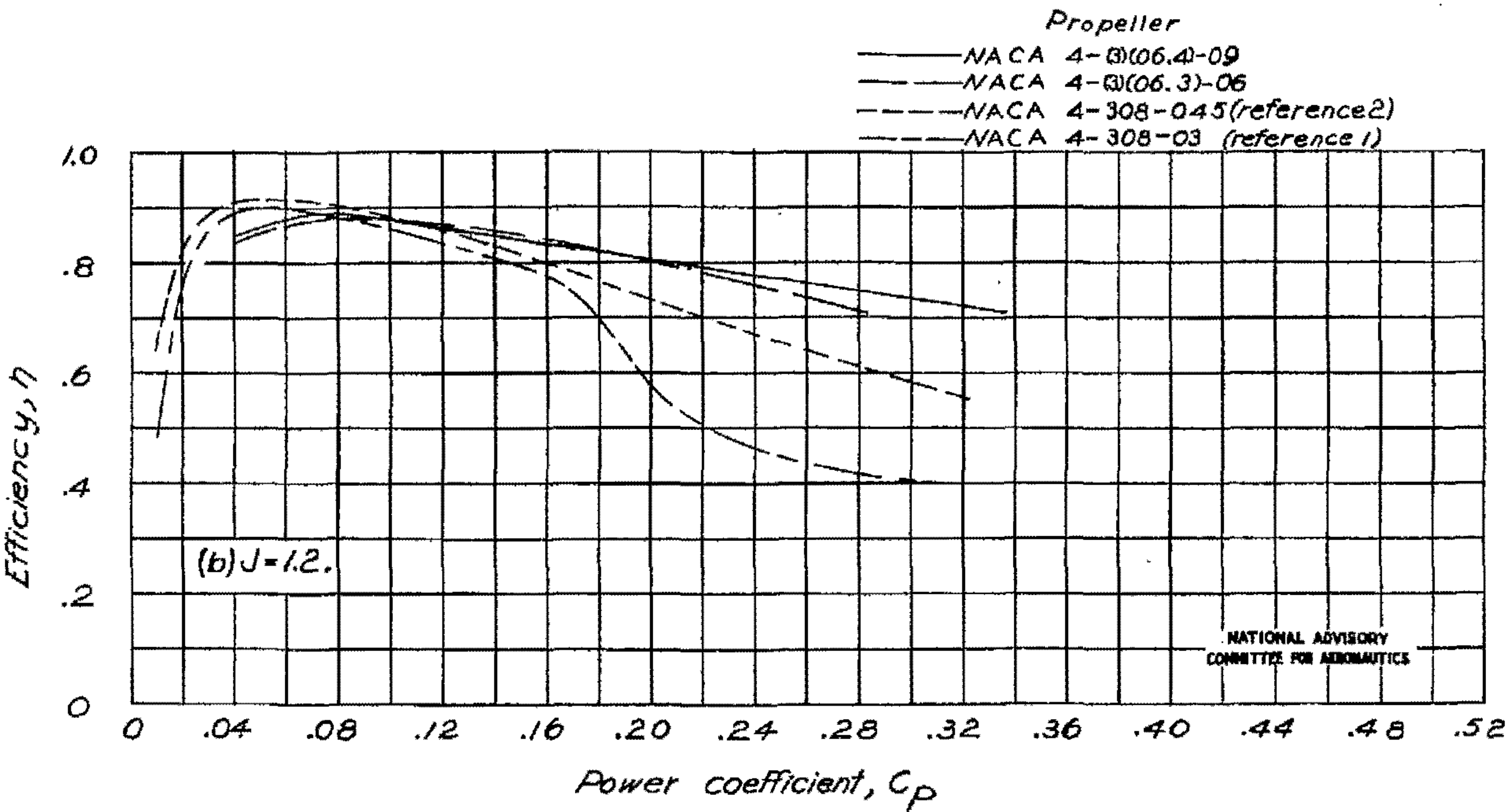


Figure 9.– Continued.

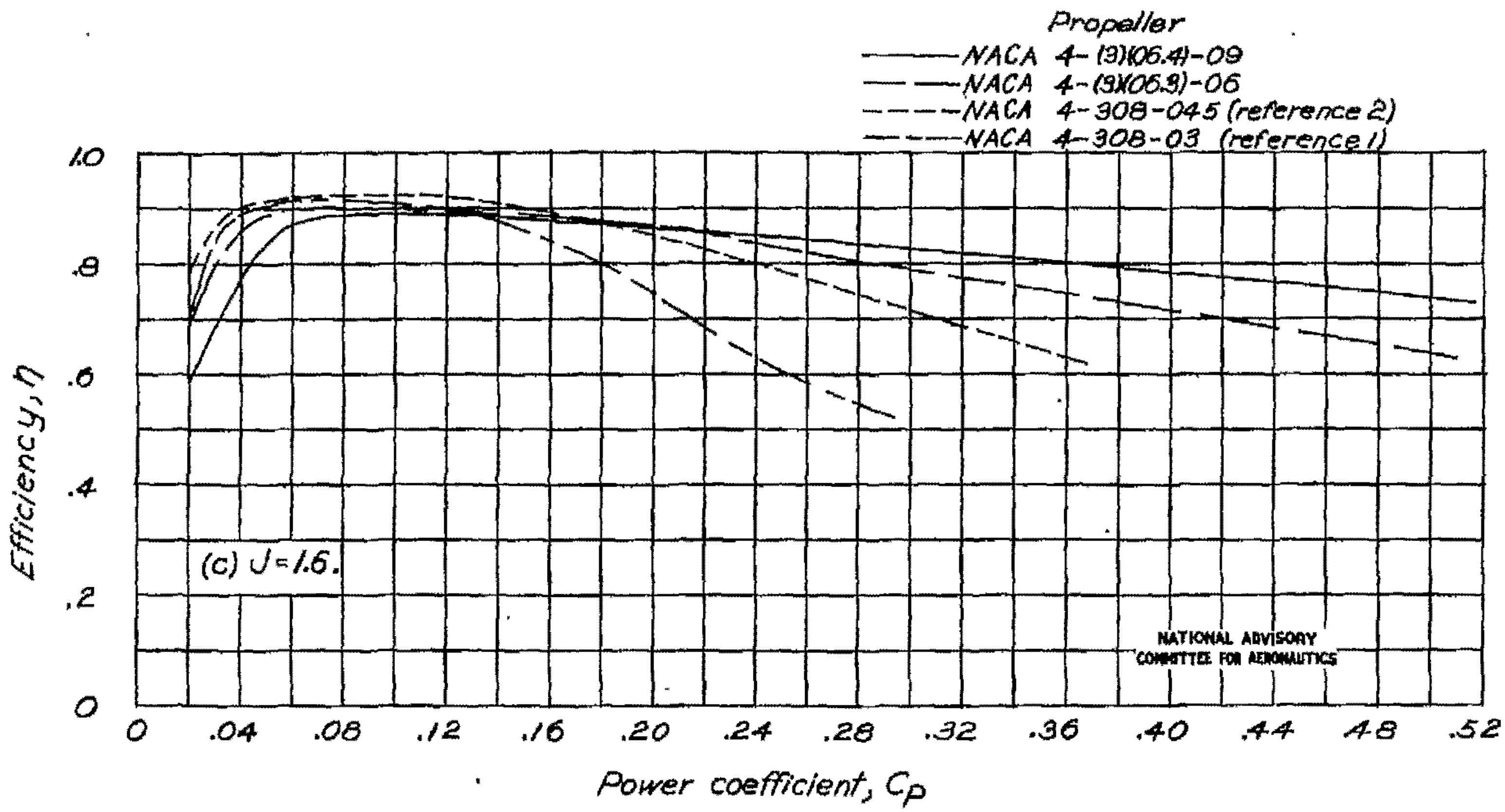


Figure 9.— Continued.

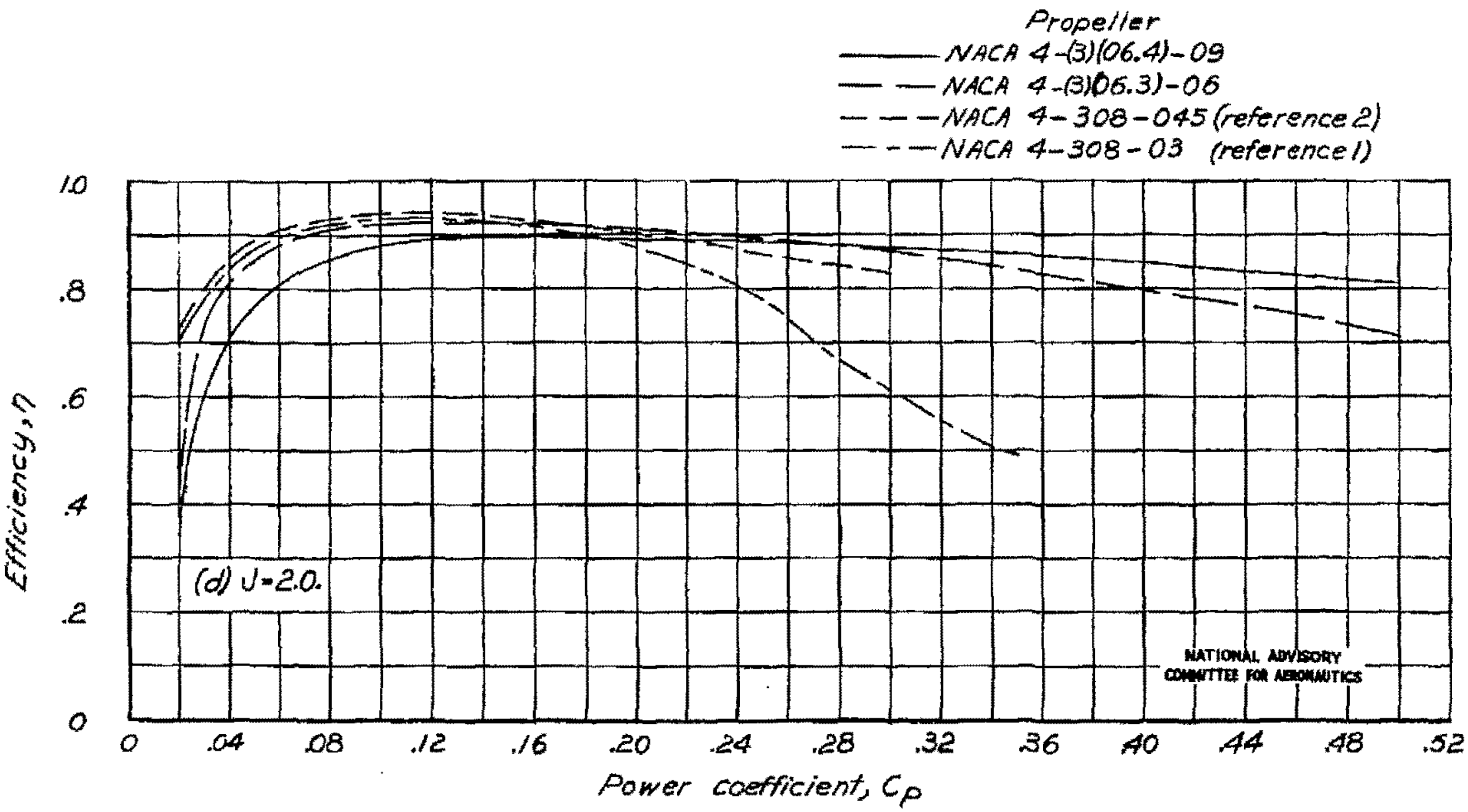


Figure 9.—Continued.

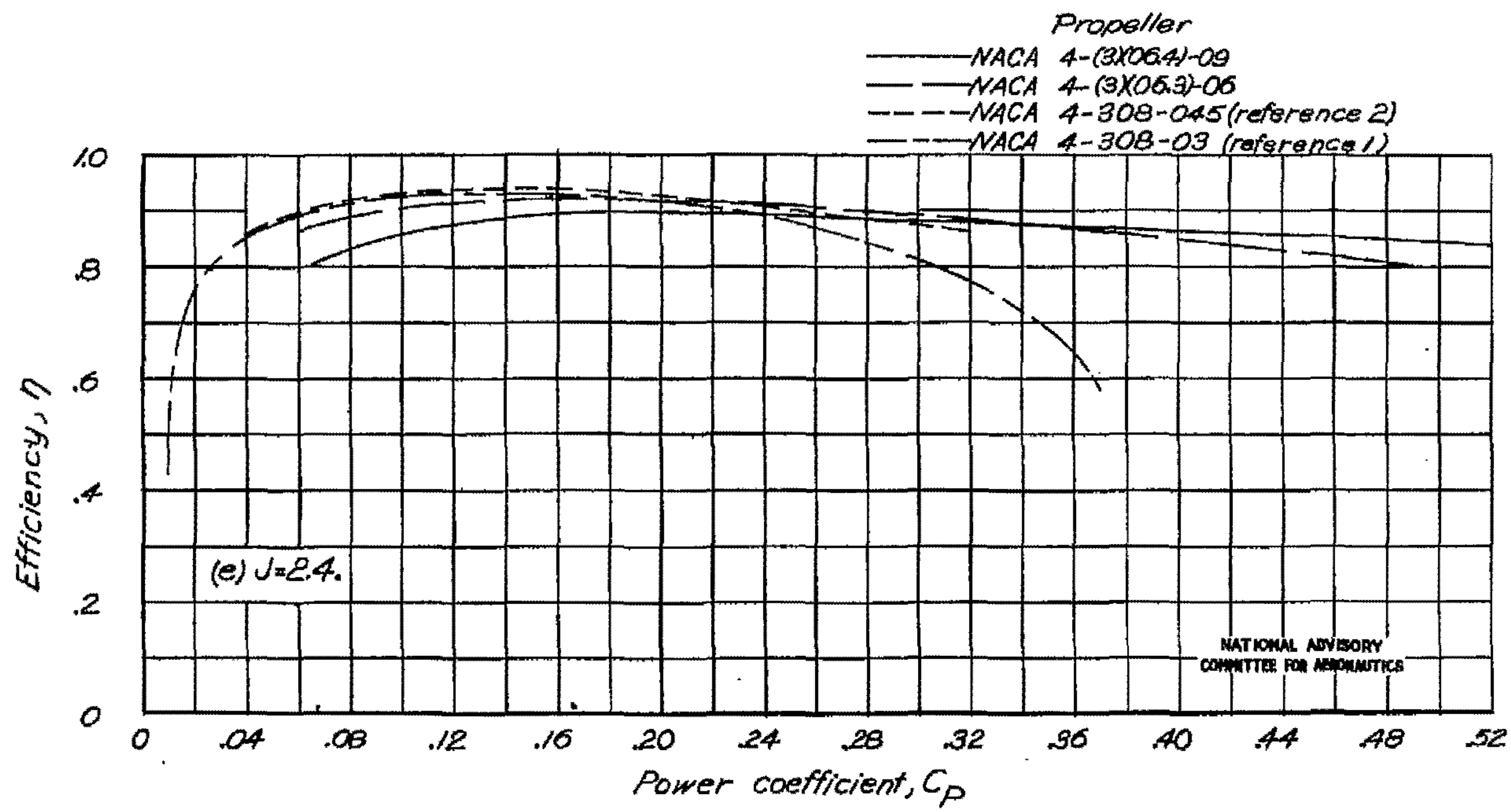


Figure 9.— Continued.

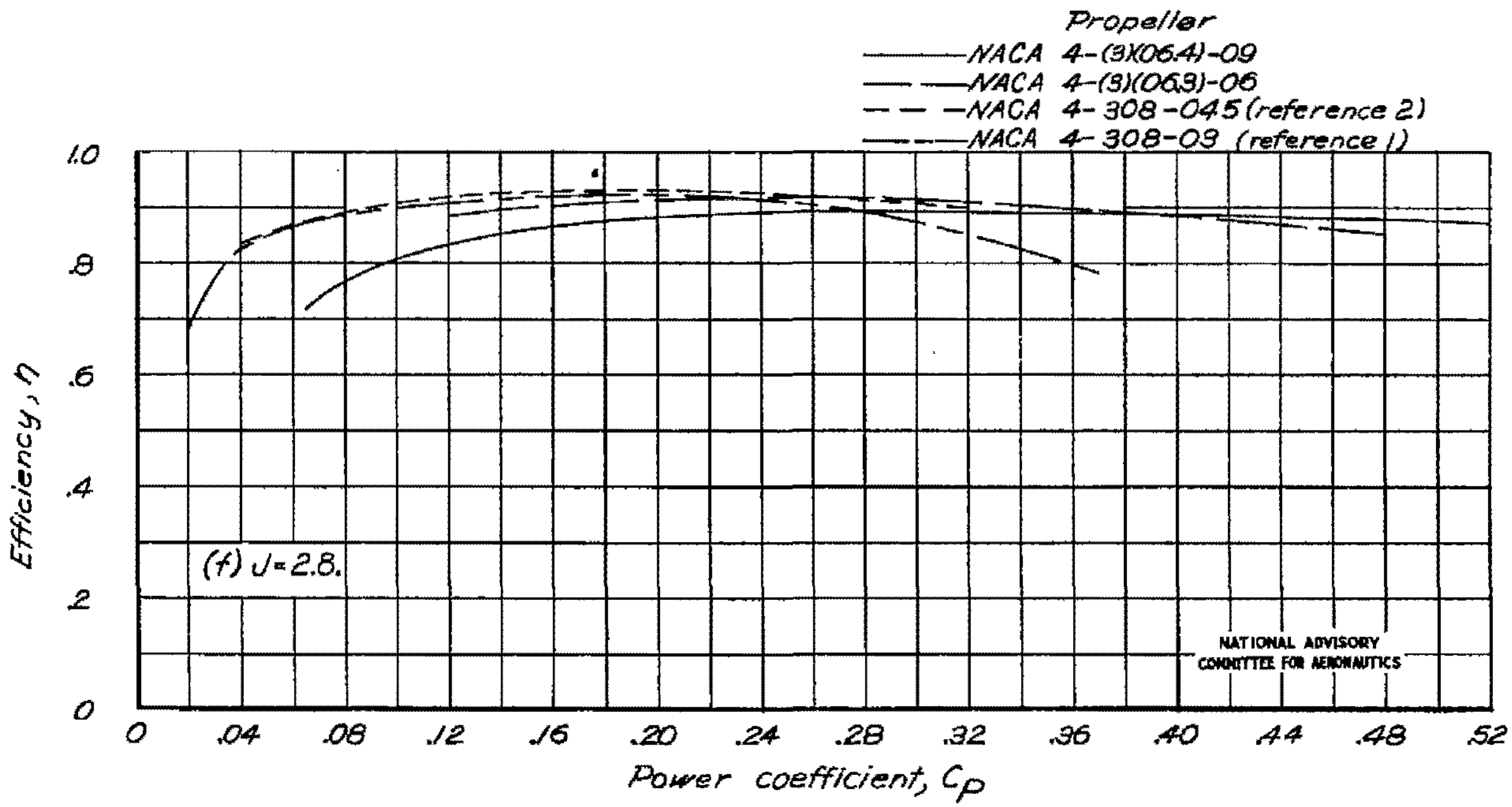


Figure 9.– Concluded.

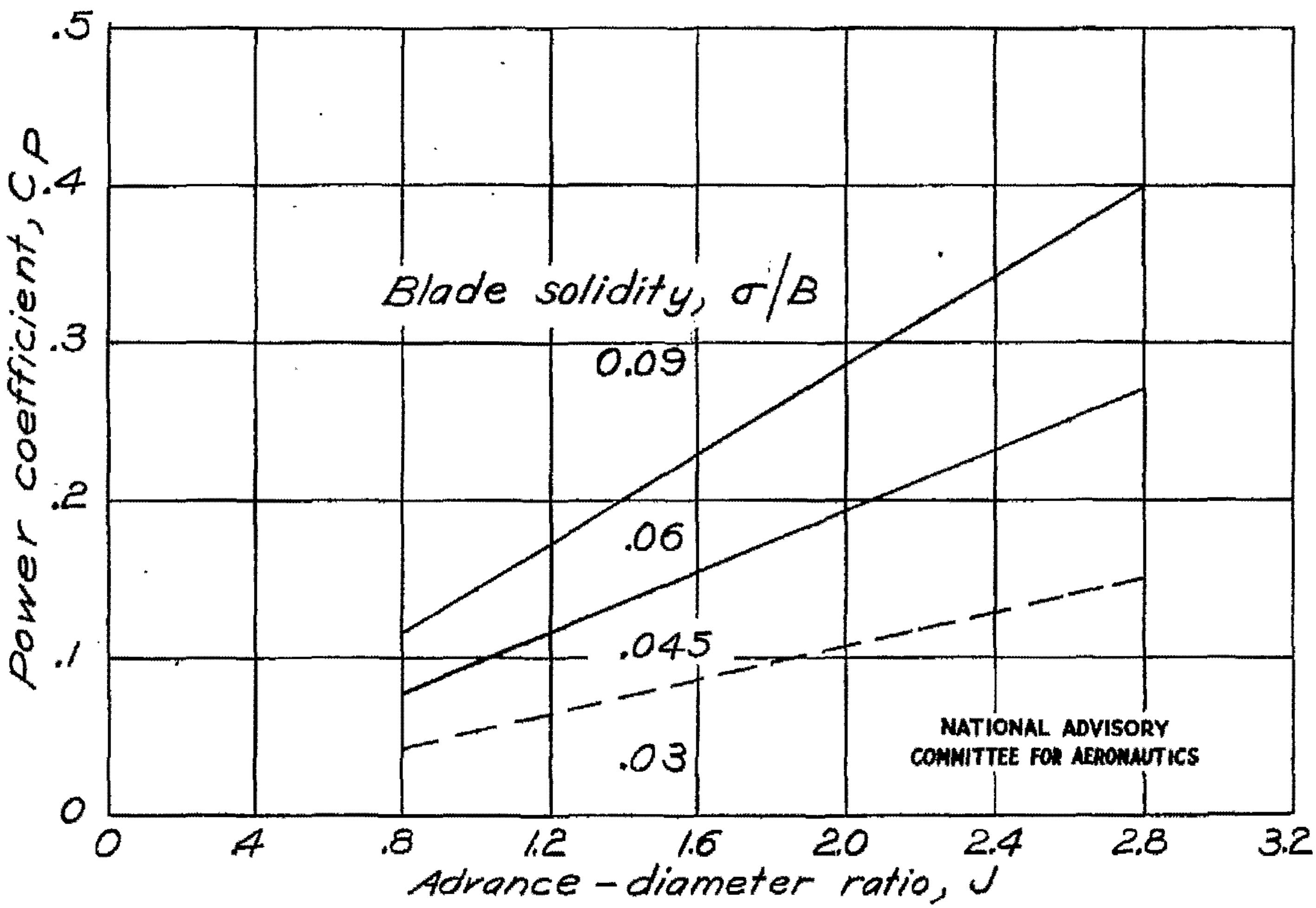
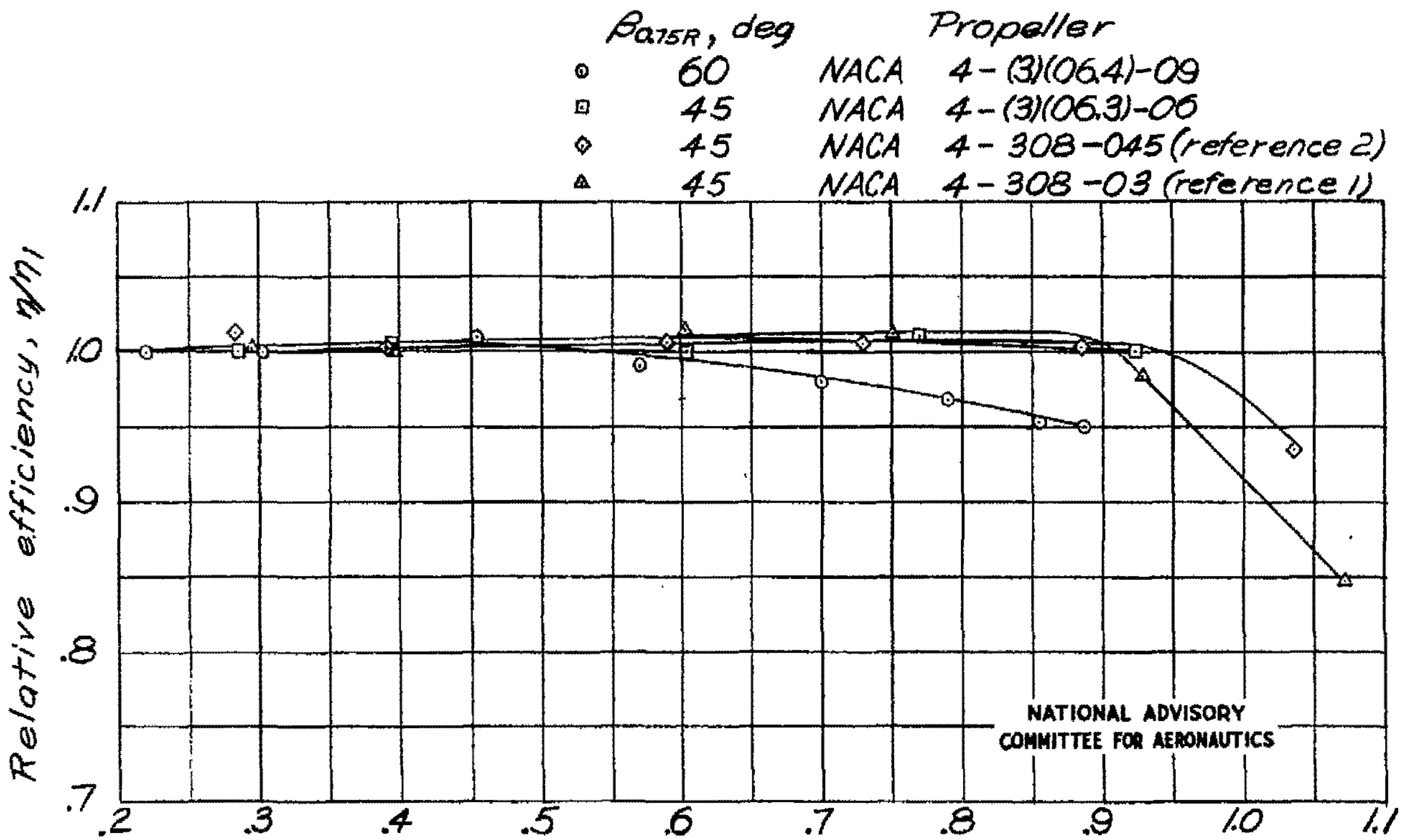
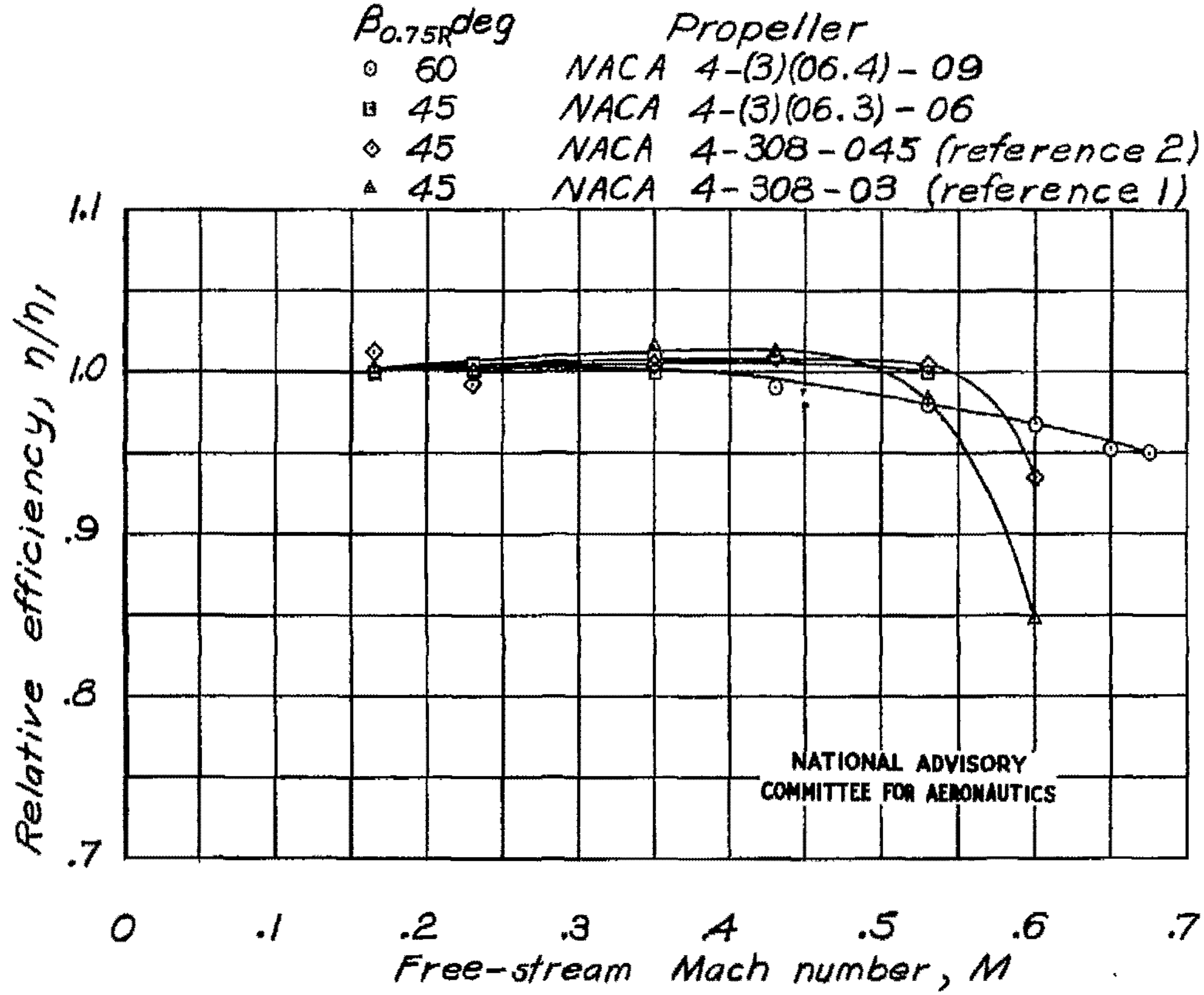


Figure 10.- Effect of blade solidity and advance-diameter ratio on the range of power coefficient for which a propeller of given solidity is more efficient than the others. $M = 0.165$.



(a) Variation of η/η_1 with M_t

Figure 11.—Effect of compressibility on maximum efficiency for approximate design blade angle.



(b) Variation of η/η_i with M.

Figure 11.- Concluded.

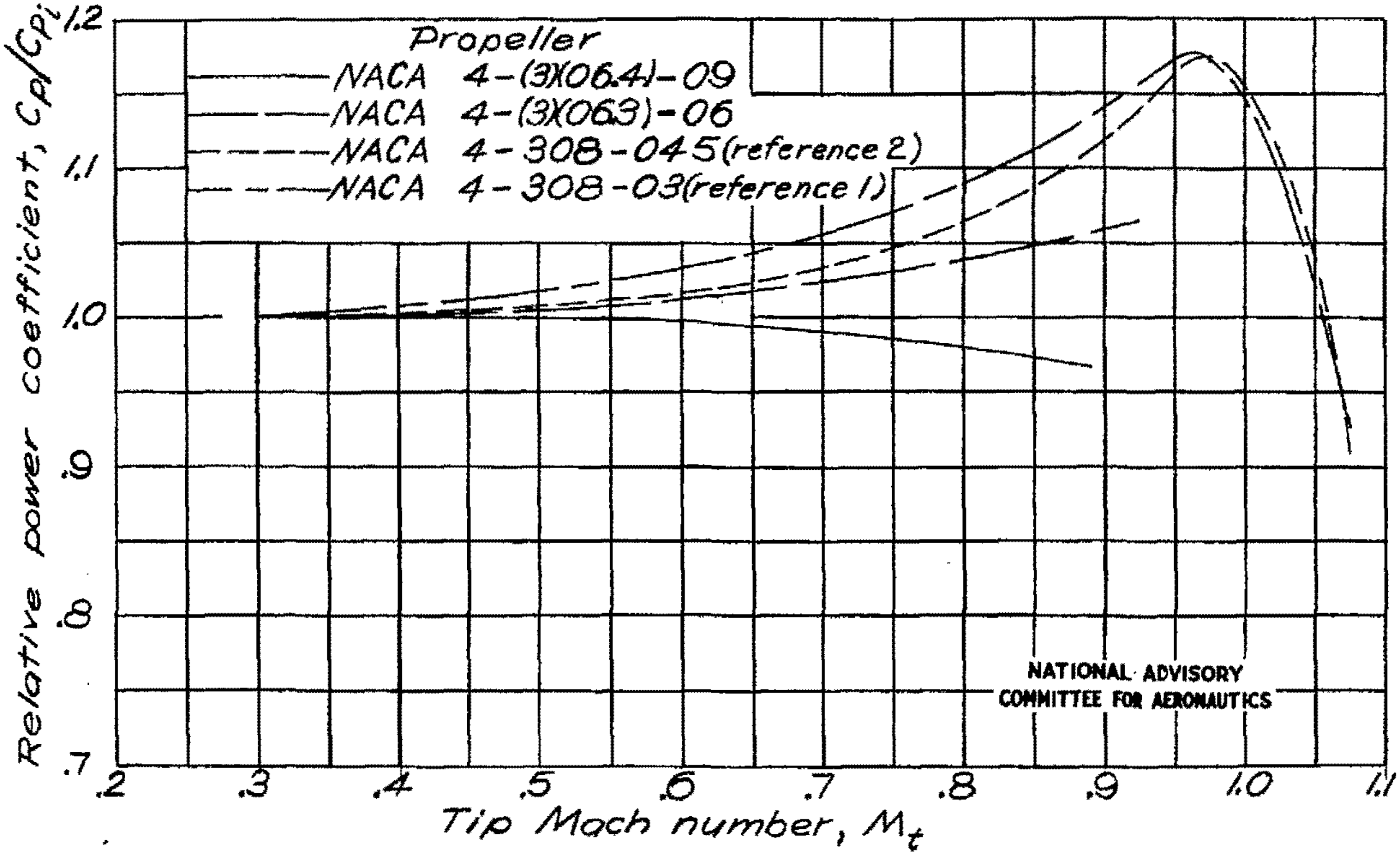
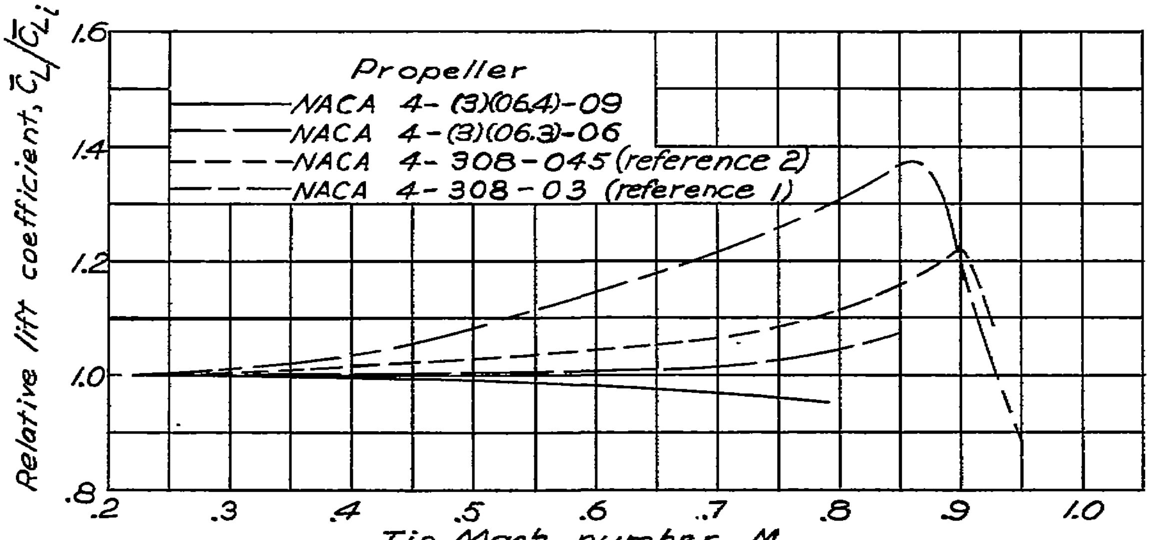
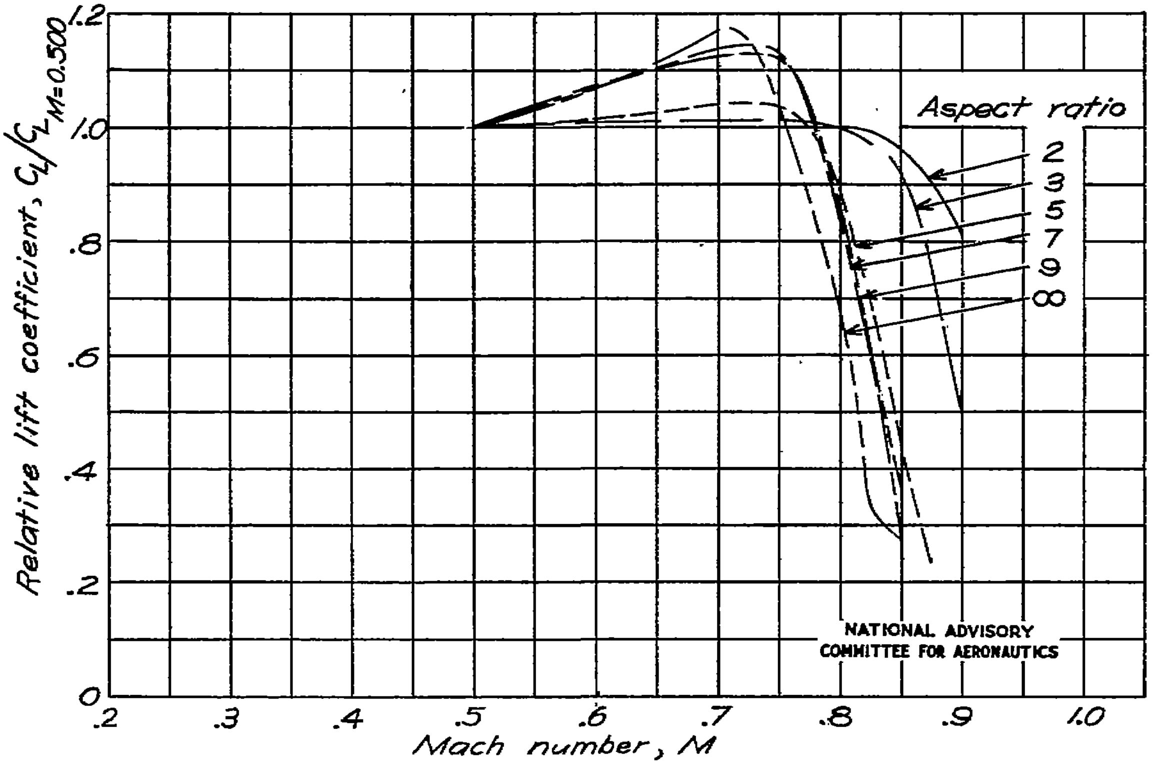


Figure 12.- Effect of compressibility on power coefficient for maximum efficiency at design blade angle and advance-diameter ratio.



(a) Average lift coefficient for propeller.



(b) Lift coefficient for wing at α 3°, data from reference 7.

Figure 13.– Effect of compressibility on lift coefficient.